1 1. Exposure Assessment Overview

This section describes EPA/OPPT's approach to assessing environmental and human exposures. For all environmental and biological media, EPA/OPPT screened, evaluated, extracted, and integrated available monitoring data. In addition, for certain media, EPA/OPPT used models to estimate environmental concentrations. Both monitoring data and modeled estimates were considered when selecting values for use in the exposure assessment.

Exposure equations and selected values used in the exposure assessment are presented in the following sections. More specific information on specific monitoring studies, summaries of modeling approaches used, and information on derivation of inputs used to model environmental concentrations and estimate age and receptor specific doses are provided in Supplementary File for General Population, Consumer, and Environmental Exposure.

After HBCD was added to EPA/OPPT's workplan list in 2012, EPA published a 2015 problem formulation prior to passage of Lautenberg amendments, and an updated scope and problem formulation document in 2017. EPA has incorporated the following refinements based on public comments and review of data since initial work began on HBCD.

- More complete assessment of human dietary exposure from multiple sources (estimates for all food groups and more specific estimates for breast milk ingestion and fish ingestion),
- Inclusion of dermal pathway,
- Inclusion of refined models used to estimate surface water and ambient air as well as sediment and indoor dust,
- Inclusion of additional contextual information from monitoring data to determine which data is likely more applicable to exposure scenarios of interest, and
- Assessment of bioaccumulation and wildlife as part of environmental exposure assessment.

1.1 1.1 Approach Used for Environmental Exposure Assessment

HBCD is highly persistent and bioaccumulative and these properties influence its potential for exposure over time. HBCD has been detected in a wide variety of environmental and biological media. Current and recent localized releases to the environment from industrial facilities, releases from indoor sources (building materials and dust), and long-range transport all contribute to levels of HBCD in the outdoor and indoor environment. However, source attribution and temporal trends from these disparate sources is complex as discussed in Section 1.1.7 Uncertainty and Variability.

EPA/OPPT screened, evaluated, and extracted identified monitoring data for surface water, sediment, soil, and targeted wildlife biota. All studies with available monitoring data and passing evaluation scores were considered to determine overall trends. In addition, key studies were identified for each media and used to inform for the selection of central tendency and high-end values. Monitoring data which had relevant contextualizing information indicating it was located near a point source was considered when selecting central tendency and high-end near-facility concentrations.

For concentrations further away from point sources and more generally applicable to the environment, all remaining monitoring data was compiled and evaluated.

Key studies were generally identified by having a high or medium evaluation score , having a large sample size, recent publication date, being conducted in the U.S. (or similar countries), and having additional discussion or interpretation of their results such as noting trends, potential sources, exposure pathways, and/or variability within or across sampling locations.

EPA/OPPT also conducted modeling to estimate concentrations of HBCD in surface water and sediment. EPA considered available biomonitoring data in wildlife and dietary patterns across trophic levels as part of its PBT assessment. These approaches were considered together to determine central tendency and high-end HBCD concentrations in surface water, sediment, soil, and targeted wildlife biota. Finally, EPA/OPPT also estimated air deposition from point sources and notes that this could contribute to elevated levels of HBCD in nearby ponds and catchment areas. This is discussed semi-quantitatively in the Section X.X soil.

EPA/OPPT characterized exposure estimates by proximity to industrial facilities. Modeled estimates are specific to different kinds of facilities for specific conditions of use, while monitoring data was more generically classified as being closer to or further away from facilities. There are several exposure assessments completed by other government organizations or within the open literature. These exposure assessments were also considered alongside monitoring and modeled values.

Table x: Overview of Approaches Used in Environmental Exposure Assessment

Type of Exposure Estimate	Summary of Approaches Used				
	Direct Use of Reported Monitoring Data	Interpretation, Scaling of Reported Monitoring Data or Completed Assessments	E-FAST Modeling	VVWM-PSC Modeling	IIOAC Modeling
Surface water near industrial facilities emitting HBCD under conditions of use	Yes		Yes	Yes	
Sediment near industrial facilities emitting HBCD under conditions of use	Yes			Yes	
Soil near industrial facilities from air deposition or with amended sludge	Yes	Yes			Yes
Surface water away from industrial sources	Yes				
Sediment away from industrial sources	Yes				
Soil away from industrial sources	Yes				
Exposures to wildlife (variable proximity)	Yes	Yes			

1.1.1 1.1.2 Aquatic Environment- Surface Water and Sediment

EPA/OPPT identified and extracted measured concentrations of HBCD in surface water in fourteen studies. This is likely due to the low water solubility of HBCD. There were also three modeled estimates of HBCD in surface water from other government agencies.

For surface water concentrations near facilities, concentrations were generally higher, with values greater than 0.1 µg/L. Reported surface water monitoring data are typically below 10 µg/L For example, reports from the UK, South Africa, and Japan range from 1.52 to 2.1 ug/L from the UK, South Africa, and Japan [ADDIN EN.CITE <EndNote><Cite><Author>EC</Author><Year>2008</Year><RecNum>226</RecNum><DisplayText>(EC, 2008)</DisplayText><record><rec-number>226</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459521865">226</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>EC,</author></authors></contributors><titles><title>Risk assessment: Hexabromocyclododecane</title></titles><dates><year>2008</year></dates><pub-location>Luxembourg</pub-location><publisher>European Commission</publisher><isbn>R044_0805_env_hh_final_ECB</isbn><urls><related-urls><url>http://echa.europa.eu/documents/10162/661bff17-dc0a-4475-9758-40bdd6198f82</url></related-urls></urls></record></Cite></EndNote>] (Oh et al. 2014) (Chokwe et al. 2015). Despite the different sampling locations and years, there is a tight range of maximum values reported across these three studies.

A risk assessment from Canada estimated HBCD concentrations ranging from 0.1 to 15 µg/L at 100 meters from a discharge pipe using a fugacity based surface water model [ADDIN EN.CITE <EndNote><Cite><Author>EC/HC</Author><Year>2011</Year><RecNum>134</RecNum><DisplayText>(EC/HC, 2011)</DisplayText><record><rec-number>134</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1454602121">134</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>EC/HC,</author></authors></contributors><titles><title>Screening Assessment Report on Hexabromocyclododecane. Chemical Abstracts Service Registry Number 3194-55-6</title></titles><dates><year>2011</year></dates><pub-location>Ottawa, Canada</pub-location><publisher>Environment Canada, Health Canada</publisher><urls><related-urls><url>http://www.ec.gc.ca/ese-ees/7882C148-8AE4-4BA4-8555-668C49F91500/HBCD%20-%20FSAR%20-%20EN.pdf</url></related-urls></urls></record></Cite></EndNote>]. These modeled estimates best approximate EPA's modeled estimates in surface water, which are discussed later in this section.

Values of surface water concentrations from areas far from facilities are generally low, with values less than 0.1 µg/L. For example, [HYPERLINK \l "_ENREF_194" \o "Venier, 2014 #130"] measured HBCD in surface water samples from the Great Lakes with HBCD detected in 14 out of 24 samples. Overall concentrations ranged from **2.0e-7 ug/L to 4.4e-6 ug/L,** with an average across detected samples of **1.2e-6 ug/L.** [HYPERLINK \l "_ENREF_84" \o "Ichihara, 2014 #228"] measured HBCD in surface water samples from 19 sampling locations in the Yodo River basin in Japan. Multiple samples were collected per sampling location and the mean values were reported by sampling location and by river. Across all 19 sampling locations, surface water concentrations ranged from 1.9e-4 ug/L to 1.4e-2 ug/L with an average concentration of 3.3e-3 ug/L. Average concentrations in the Kanzaki River, Yodo River, and Yamato River were 9.1e-4, 7.6e-4, and 6.7e-3 ug/L. The authors also reported flow rates and estimated pollutant loads. It is noteworthy, that the lowest flow river, the Yamato River, had the highest HBCD

concentration. Charts and tables that provide additional details for surface water data are presented in the Supplementary File.

EPA/OPPT identified over fifty monitoring studies that contained information on HBCD in sediment. This is likely due to the high KoC of HBCD.

Reported concentrations in sediment span orders of magnitude and range from <1 µg/kg dw to <1,000 µg/kg dw, with the highest concentrations recorded near industrial areas or downstream of facilities that are associated with the manufacture, processing, use of brominated flame retardants (BFRs) or BFR containing materials. This overall trend suggests that some facilities or industries likely serve as point sources for the release of HBCD to the environment.

Two studies by Guerra et al were identified as key studies to characterize near-facility sediment concentrations. These studies, noted the same trend with higher sediment concentrations located near point sources, decreasing sediment concentrations downstream from point sources, and non-detects upstream or further away from point sources. [HYPERLINK \l "_ENREF_68" \o "Guerra, 2009 #142"] identified a sampling site near a point source (C3) with HBCD concentrations in surficial sediment ranging from 514-2,430 ug/kg. Concentrations of HBCD decreased to 90-866 ug/kg 27-30 km downstream. HBCD was not detected 60 km downstream or at upstream locations. Similarly, [HYPERLINK \l "_ENREF_69" \o "Guerra, 2010 #230"] identified a sampling site (S5) near a point source with the highest HBCD concentrations reported with 1,873 ug/kg. Sites 27 and 60 km downstream (S6-S7) had HBCD concentrations of 91 and 64.6 ug/kg respectively.

For central tendency sediment concentrations, the [HYPERLINK \l "_ENREF_48" \o "EC, 2008 #226"] assessment characterized sediment concentrations both near point sources and away from point sources. Their meta-analysis across 16 studies reported a range from 0.05 to 511 µg/kg. Overall the data set is skewed with median HBCD concentration of 1.5 ug/kg, lower than the mean HBCD concentration of 31 ug/kg. The 90th percentile HBCD concentration was estimated as 100 ug/kg.

For this assessment, when looking across all sediment studies, the overall results show that most data falls within the range of 1 and 10,000 with some data points in a small subset of studies falling below and above this range. Charts and tables that provide additional details for sediment data are presented in the Supplementary File.

EPA/OPPT also used models to estimate surface water and sediment concentrations. EPA's Exposure and Fate Assessment Screening Tool, Version 2.0, (E- FAST2) was developed to support EPA assessments of potential environmental exposures. For exposure characterization, the E- FAST2 model was used to estimate HBCD surface water concentrations based on estimated water releases from facilities that manufacture or process HBCD. The exposure scenarios included in the E- FAST2 model contain default parameter values that allow for exposure estimations considering dilution.

There are a variety of other surface water models that consider additional processes that occur such as partioning, volatilization, and degradation. Variable flow throughout a river and differences in river characteristics, turbidity, channel characteristics, meteorology can also be considered. As these additional processes are considered, complexity of modeling increases.

Water dilution models can be used to determine the concentration of a chemical in the surface water after a source emits the chemical into a water body. The volume of a river varies over time with different flows expected seasonally and from year to year. Simple dilution models can take this into account but

do not account for partitioning between compartments within a surface water body or degradation over time in different media.

E- FAST2 includes a Probabilistic Dilution Model (PDM) which predicts the number of days per year in which a designated exposure, or effect level (*i.e.*, concentration of concern) will be exceeded in ambient waters as a result of chemical discharges (effluents) released from a facility. PDM analyses can be performed on stream reaches with measured flow data or stream reaches that incorporate estimated streamflow values. The PDM model provides chronic risk estimates that are derived from a simple mass balance approach of chemical dilution/emulsion into stream water; however, the input parameters are not single point estimates.

In reality, streams exhibit highly variable seasonal flow patterns. In addition, manufacturing processes include various operating procedures that can change intermittently, thereby affecting effluent flow rates and the total amount of chemical released to the environment over a given time interval. The PDM incorporates probability distributions from Monte Carlo simulations as analysis inputs for calculating the resulting probability distribution for the chemical concentration that may be seen in stream waters. Ultimately it predicts the number of days per year in which the modelled stream concentrations are expected to exceed the designated effect levels (i.e., COCs) identified for aquatic organisms based on the total amounts of chemical released per day [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>2007</Year><RecNum>231</RecNum><DisplayText>(U.S. EPA, 2007)</DisplayText><record><rec-number>231</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523433">231</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Exposure and fate assessment screening tool (E-FAST): Version 2.0, documentation manual</title></titles><dates><year>2007</year></dates><urls></urls></record></Cite></EndNote>]

A summary of the input data used for the E- FAST2 model and a summary table which includes site specific input parameters is provided in the Supplementary File.

The limitations associated with use of the E- FAST2 model relate to the assumptions made regarding use of sector-based flow information as a surrogate for site-specific flow information, as well as lack of partitioning and degradation parameters that could be employed in a higher-tier model.

Since the E- FAST2 model incorporates defaults that encompass either a combination of upper percentile and mean exposure parametric values, or all upper percentile parametric values, the resulting model predictions represent high- end exposures estimates. EPA/OPPT acknowledges the conservative nature of this approach. [REF _Ref449618127 \h * MERGEFORMAT] provides flow values used as inputs for the E-FAST model.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: Flow values used for the E-FAST model

	Harmonic Mean Flow Million Liters per Day (MLD) (50^{th})	**7Q10 Flow MLD (50^{th})**
SIC Code- Plastic Resins	1321.8	403.46
SIC Code- Industrial POTW	288	78.18

Note, surface water concentrations based on 7Q10 flows were considered for ecological exposure assessment. Surface water concentrations based on harmonic mean flows from long-term releases were considered for estimates of fish tissue concentrations. Note, 50^{th} percentile values and 10^{th} percentile

flow values are available for the SIC codes noted in [REF _Ref449618127 \h * MERGEFORMAT]. The 50th percentile values were chosen for comparison with monitoring data in this assessment. In general, the 10th percentile flow values are approximately a factor of ten lower than 50th percentile flows. The PDM estimates the number of days that the time-varying surface water concentration is above the concentration of concern as it varies around these 50th and 10th percentile values. The number of days exceeded increases with lower flows. From Table x-x [REF _Ref449618149 \h * MERGEFORMAT], high-end PDM values using 10th percentile flows are not presented and average PDM values using 50th percentile flows are used instead.

E-FAST2 was used to estimate surface water concentrations for estimated releases. It should be noted that these estimates are based on dilution and incorporate HBCD in both the dissolved and particulate phase. However, low-flow stream inputs combined with high-release estimates may yield overly conservative surface water concentrations. See Table x-x for modeled surface water estimates.

Estimated HBCD Surface Water Concentrations using E-FAST

SCENARIO NAME	water releases	Harmonic Mean SWC (ug/L) 50th	Harmonic Mean SWC (ug/L) 10th	7Q10 SWC (ug/L) 50th	7Q10 SWC (ug/L) 10th	Days exceeded (HIGH)	Days exceeded (Average)
1. Import/Repackaging	yes	0.44	3.18	1.61	16.24	58 of 60	24 of 60
2. Compounding of Polystyrene Resin to Produce XPS Masterbatch	yes	0.01	0.06	0.03	0.31	6 of 60	1 of 60
3. Manufacturing of XPS Foam using XPS Masterbatch (CT)	yes	0.17	1.23	0.62	6.26	52 of 60	15 of 60
3. Manufacturing of XPS Foam using XPS Masterbatch (HE)	yes	1.60	11.64	5.90	59.41	n/a	n/a
4. Manufacturing of XPS Foam using HBCD Powder (CT)	yes	0.001	0.008	0.004	0.039	0 of 60	0 of 60
4. Manufacturing of XPS Foam using HBCD Powder (HE)	yes	0.16	1.17	0.59	5.97	52 of 60	15 of 60
5. Manufacturing of EPS Foam from Imported EPS Resin beads	yes	5.69	41.39	20.96	211.20	60 of 60	60 of 60
6. Manufacturing of SIPs and Automotive Replacement Parts (CT)	yes	0.002	0.01	0.01	0.06	1 of 60	0 of 60
6. Manufacturing of SIPs and Automotive Replacement Parts (HE)	yes	0.01	0.05	0.03	0.26	19 of 60	2 of 60
7. Installation of Automotive Replacement Parts	no						
8. Installation of Insulation in Buildings (Commercial)	yes	0.001	0.01	0.004	0.11	n/a	n/a
8. Installation of Insulation in Buildings (Residential)	yes	0.00	0.00	0.00	0.02	n/a	n/a
9. Service Life	no						
10. Demolition and Disposal of Insulation in Buildings	not on per site basis						
11. Recycling of EPS Foam	yes	0.004	0.03	0.01	0.15	2 of 60	0 of 60
12. Formulation of Coatings and solder	no						
13. Application of Coatings (Commercial)	yes	1.00	11.34	4.70	118.87	n/a	n/a
13. Application of Coatings (Residential)	yes	0.03	0.36	0.15	3.77	n/a	n/a
14. Use of Solder	yes	0.00	0.00	0.00	0.01	0 of 60	0 of 60

Water dilution models can be used to determine the concentration of a chemical in the surface water column after a source emits the chemical into a water body. The volume of a river varies over time with different flows expected seasonally and from year to year. The E-FAST2 model does not account for partitioning between dissolved and suspended sediment within the water column or between the water column and the benthic environment. The benthic environment is made up of pore water and settled sediments.

Site-specific parameters influence how partitioning occurs over time. For example, the concentration of suspended sediments, water depth, and weather patterns all influence how a chemical may partition between compartments. Physical-chemical properties of the chemical itself also influence partitioning and half-lives into environmental media. HBCD has a KOC of 100,000 indicating a high potential to sorb to suspended particles in the water column and settled sediment in the benthic environment.

Canada considered these parameters when estimating surface water and sediment concentrations of HBCD in rivers receiving HBCD from point sources. Surface water and sediment concentrations were estimated at 100 m from the facility and 5,000 m from the facility using a 10 box fugacity-based model ([HYPERLINK \l "_ENREF_49" \o "EC/HC, 2011 #134"]. These modeled estimates are presented in Figure 1.1. It is noteworthy that this modeling was conducted when releases to surface water from uses of HBCD were likely higher than they are today.

EPA also modeled dissolved water and settled sediment concentrations using surface water release estimates tailored for this assessment. EPA used the Variable Volume Water Body Model (VVWM)- Point Source Calculator (PSC) to complete this modeling (EPA 2018). The PSC is a tool designed to estimate time-varying surface water concentrations of a chemical directly applied to a water body, including but not limited to river segments. Loading into the river can be varied daily, set up to be discrete one-time events, or repetitive events over most or all of the year. The PSC is a graphical user interface which gathers the user's inputs and runs USEPA's VVWM. Required inputs are the same as those for the VVWM, but the PSC graphical interface facilitates user interaction for the direct-application and allows model inputs to be defined by the user. Time-varying surface water concentrations can be averaged over variable time periods for comparison to concentrations of concern. For example, 21-day average surface water concentrations and 28-day average sediment concentrations were used for EPA's modeling assessment.

Surface water flow can be set up to be constant flow or use time-varying flows. Since site-specific information was not available for these facilities, constant flows matching the SIC-based flow values used in E-FAST were selected. Suspended sediment values are highly variable and are influenced by stream flow, land cover, and river conditions. A KoC value of 100,000 was chosen based on measured data. Note, a weather file is also needed to run VVWM-PSC. This incorporates variable flow volume through precipitation events. However, variation through precipitation alters stream flow much less than variations in stream flow from other factors. Use of a constant flow which varied across scenarios was chosen. [REF _Ref449618168 \h * MERGEFORMAT] displays the inputs used to run the VVWM-PSC for HBCD.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: Inputs to run VVWM-PSC

Input	Type of Input	Value	Units, Comments	Reference
Sorption Coefficient (KoC)	Chemical	100,000	ml/g	**STUDY**
Chemical half-life in all media	Chemical	1000	Days	EPI-suite, p/chem property
Molecular weight	Chemical	641.7	g/mol	EPI-suite, p/chem property
Vapor pressure	Chemical	5.4e-9	Torr	EPI-suite, p/chem property

Water solubility	Chemical	0.066	Mg/L	EPI-suite, p/chem property
Heat of enry	Chemical	41570	J/mol	EPI-suite, p/chem property
Loading schedule	Chemical	0, 7, 0 0, 5, 2 10, 1, 1000	Offset, days on, days off Represents 365 day/year Represents 250 day/year Represents 1 day/year	
River width	Environment	8	Meters	
River depth	Environment	2	Meters	
River length	Environment	100	Meters	
Flow rate	Environment	Varies	See [REF _Ref449618127 \h * MERGEFORMAT]	
DFAC	Environment	1.19	Photolysis parameter: Represents the ratio of vertical path lengths to depth	PSC-VVWM User Guide or references within
Water column suspended sediment	Environment	50	mg/L	Dodds et al 2004
Chlorophyll	Environment	0.005	mg/L	PSC-VVWM User Guide
Water column fraction organic content	Environment	0.04	fraction	PSC-VVWM User Guide
Water column dissolved oxygen content	Environment	5.0	mg/L	PSC-VVWM User Guide
Water column biomass	Environment	0.4	mg/L	PSC-VVWM User Guide
Benthic depth	Environment	0.05	m	PSC-VVWM User Guide
Benthic porosity	Environment	0.5		PSC-VVWM User Guide
Bulk density	Environment	1.35	g/cm3	PSC-VVWM User Guide
Benthic fraction organic content	Environment	0.04		PSC-VVWM User Guide
Benthic dissolved oxygen content	Environment	5.0	mg/L	PSC-VVWM User Guide
Benthic biomass	Environment	0.006	g/m2	PSC-VVWM User Guide
Mass transfer coefficient	Environment	1e-8	m/s	PSC-VVWM User Guide

Figure x-x has the estimated HBCD sediment concentrations from VVWM-PSC. Note, that the overall surface water column concentrations are the same. However, 75% of the HBCD concentration was estimated to be in the dissolved phase using the modeling inputs described above. The default values, such as suspended sediment concentration, fraction organic content, chlorophyll, and biomass content also influence distribution. A targeted sensitivity analysis showed that KoC, half-life in sediment, fraction organic content, and suspended solids are parameters that tend to have more of an impact on sediment concentrations. EPA considered variation of some of the more sensitive parameters, but found results using different inputs showed similar magnitude and trends as the results presented. This is likely because alteration of multiple parameters many have an off-setting impact.

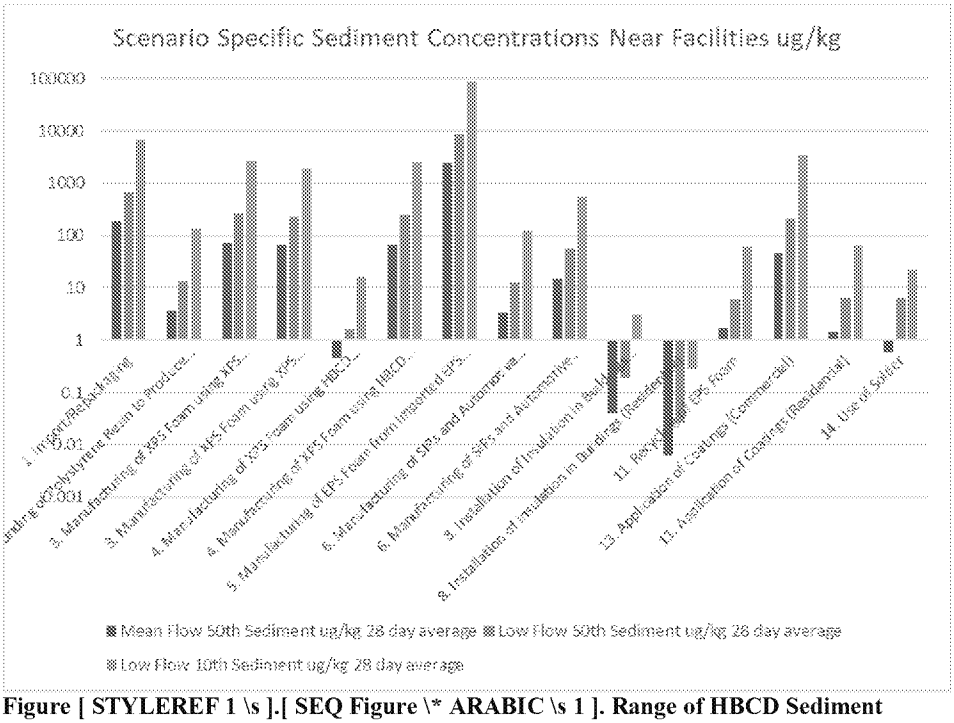


Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1]. Range of HBCD Sediment Concentrations near Facilities

1.1.2 1.1.3 Terrestrial Environment- Soil and Deposition from Air

EPA/OPPT identified 17 studies where concentrations of HBCD in soil were extracted. Wu et al 2016, reported soil concentrations across a wide variety of land-use types with higher concentrations reported near industrial areas. Wu et al 2016 reported soil concentrations ranging from 0.3 to 249 µg/kg. The soil concentration was influenced by the sample depth as well as proximity to facilities. For soil concentrations applicable to the general population, [HYPERLINK \l "_ENREF_146" \o "Tang, 2014 #7"] collected 90 samples across the Ningbo Region of China. Samples collected in residential and agricultural areas ranged from ND to 46 µg/kg.

Another pathway where HBCD can reach soil is through application of biosolids to agricultural lands. Health Canada used a modeling approach that resulted in an estimated soil concentration of 300 µg/kg (HC 2011). This value is on the high-end of reported soil monitoring data. The approach used a conservative value for biosolids concentration of 100,000 µg/kg based on LaGuardia et al. (2010). This value remains the highest value reported to date, with other studies reporting lower biosolids concentrations.

Due to the lack of measured soil data, PECs were calculated for tilled agricultural soil and pastureland based on Equation 60 of the European Commission Technical Guidance Document (TGD; European Communities 2003), as follows:
PECsoil = (Csludge x ARsludge) / (Dsoil x BDsoil)
where:
PECsoil = PEC for soil (mg/kg)
Csludge = concentration in sludge (mg/kg)
ARsludge = application rate to sludge amended soils (kg/m2/yr); default = 0.5 from Table A-11 of TGD
Dsoil = depth of soil tillage (m); default = 0.1 m from Table 11 of TGD
BDsoil = bulk density of soil (kg/m3); default = 1700 kg/m3 from Section 2.3.4 of TGD

The equation assumes no losses from transformation, degradation, volatilization, erosion or leaching to lower soil layers. Additionally, it is assumed there is no input of HBCD from atmospheric deposition and there are no background HBCD accumulations in the soil. To examine potential impacts from long-term application, an application time period of 10 consecutive years was considered. The geometric mean of sludge concentrations reported by La Guardia et al. (2010), 10.04 mg/kg dw, was used as Csludge in the calculation. Data were converted from ng/g TOC to mg/kg dw using the organic carbon content of the sludge specified in the study.

One of the limitations of Health Canada's modeling approach is that it not consider air deposition or background soil concentration. EPA/OPPT calculated the resulting soil concentration from air deposition in scenario specific release estimates using the following equations:

<insert equations>

The overall magnitude of soil concentrations solely due to air deposition is generally low, <1 ug/kg for the highest release scenario. Further, background soil concentrations based on the soil monitoring data are well below 300 ug/kg and closer to 1-10 ug/kg. Therefore, an estimated soil concentration from biosolids application, air deposition, and background values would be slightly, but not appreciably, higher than 300 ug/kg.

Charts and tables that provide additional details for sediment data are presented in the Supplementary File.

1.1.3 1.1.4 Assessment of Persistence, Bioaccumulation and Exposure in Targeted Wildlife Biomonitoring

There are numerous studies examining the occurrence of HBCD in a wide range of wildlife biota across multiple trophic levels. Most of the monitoring samples reported HBCD in lipid weight while some reported in wet weight. Releases of HBCD to the environment over time result in sustained or persistent concentrations that are available for uptake by a wide variety of species. Some studies have attempted to note temporal and spatial trends of HBCD concentrations in biota [Reference] [Reference], while other studies have attempted to show trends across trophic levels [Reference]. Charts and tables summarizing occurrence of HBCD in aquatic and terrestrial biota are presented in the Supplementary File.

1.1.4 1.1.5 Summary of Results for Environmental Exposure Assessment

For near-facility concentrations, HBCD monitoring data was compared with modeled estimates of environmental concentrations based on estimated release data. Monitoring data which had relevant contextualizing information indicating it was also located near a source was considered when selecting central tendency and high-end near-facility concentrations. Monitoring data was also considered when selecting central tendency and high-end concentrations away from point sources. The overall range of data from all studies, range of central tendency, range and central tendency estimates of key studies summarized in previous sections, and sampling locations and sample size were considered. While a meta-analysis using raw data would have provided a more robust approach, raw data was generally not available for most studies.

	Surface Water Concentration (µg/L)	**Sediment Concentration (µg/kg)**	**Soil Concentration (µg/kg)**
E-FAST modeled estimates range (median) for all mean-flow estimates across scenarios	0.0001-41.39 (0.03)	n/a	n/a
E-FAST modeled estimates range (median) for all low-flow estimates across scenarios	(0.0007- 211.2 (0.15)	n/a	n/a
Modeled Estimates from Canada 2011 (100 meters from facility)	Raw materials handling 0.5-15 Compounding 0.1-1.3	Raw materials handling 3,600-108,200 Compounding 330-9,920	n/a
Modeled Estimates from Canada 2011 (5 km from facility)	Raw materials handling 0.3-10 Compounding 0.03-0.9	Raw materials handling 2,600-76,700 Compounding 230-7,030	n/a
Modeled Estimates VVWM-PSC, Range (median) for all mean-flow estimates	21-day average-dissolved 5E-6 to 0.61 (0.001)	28 day average 0.006 to 2420 (3.6)	n/a
Modeled Estimates VVWM-PSC, Range (median) for all low-flow estimates	21-day average dissolved 2E-5 to 22.7 (0.03)	28 day average 0.027 to 89,000 (94.3)	n/a
Range of all Monitoring Data	0.00003-10	0.000009-330,000	ND to 225,000
Range of central tendency Monitoring Data	0.00175- 0.15	0.00082-451	0.03- 7,458 (48)

Range (central tendency) of key studies near point sources) **A) EC 2008** **B) Guerra et al. 2009** **C) Guerra et al. 2010** **D) Li et al. 2012** **E) Tang et al. 2014**	A)1.52 to 10	B) 12,192-389,700 C) 514-2,430 D) 64.4-1,873	E) 0.88 – 6,901 F) 6 -106
Range (central tendency) of key studies away from point sources **A) Venier et al. 2014** **B) Ichihara et al. 2014** **C) EC 2008** **D) Tang et al. 2014**	A) 2.0e-7 - 4.4e-6 B) 1.9e-4 – 1.4e-2 (3.3e-3)	C) 0.05-511 (31)	D) ND - 46

1.1.5 1.1.6 Values used in the Environmental Exposure Assessment

The following values in Table X were used in the environmental exposure assessment. Note, that soil concentrations were also used for the assessment of human exposure and are further discussed in Section XX.

Table X.

SCENARIO NAME	1-day HBCD surface water (river)-mean flow ug/L	21 day average HBCD surface water (river) mean flow ug/L	1-day HBCD surface water (river)-low flow ug/L	21 day average HBCD surface water (river) low flow ug/L	steady state pond concentration from air ug/L	28 day HBCD sediment concentration (river) mean flow ug/kg	28 day HBCD sediment concentration (river) low flow ug/kg	steady state sediment concentration from air ug/kg	steady state soil concentration from air ug/kg
1. Import/Repackaging	0.328	4.7E-02	9.46	1.74	1.8E-04	186	6,840.0	2.8E-03	2.2E-03
2. Compounding of Polystyrene Resin to Produce XPS Masterbatch	0.006	9.2E-04	0.18	0.03	8.0E-07	3.6	132.0	1.2E-05	9.5E-06
3. Manufacturing of XPS Foam using XPS Masterbatch (CT)	0.126	1.8E-02	3.65	0.67	4.4E-06	71.7	2,640.0	6.7E-05	5.1E-05
3. Manufacturing of XPS Foam using XPS Masterbatch (HE)	1.196	5.7E-02	33.00	1.70	2.7E-05	65.8	1,920.0	4.2E-04	3.2E-04
4. Manufacturing of XPS Foam using HBCD Powder (CT)	0.001	1.1E-04	0.02	0.004	8.2E-07	0.446	16.4	1.3E-05	9.7E-06
4. Manufacturing of XPS Foam using HBCD Powder (HE)	0.120	1.7E-02	3.47	0.64	7.3E-07	68.4	2,520.0	1.1E-05	8.5E-06
5. Manufacturing of EPS Foam from Imported EPS Resin beads	4.269	6.1E-01	122.62	22.71	4.2E-04	2420	89,000.0	6.5E-03	5.0E-03
6. Manufacturing of SIPs and Automotive Replacement Parts (CT)	0.001	8.6E-04	0.04	0.03	2.7E-04	3.38	124.0	4.1E-03	3.2E-03
6. Manufacturing of SIPs and Automotive Replacement Parts (HE)	0.005	3.8E-03	0.18	0.14	6.7E-04	15.1	554.0	1.0E-02	7.9E-03

7. Installation of Automotive Replacement Parts									
8. Installation of Insulation in Buildings (Commercial)	0.001	3.2E-05	0.02	0.002	1.2E-06	0.0415	3.0	1.9E-05	1.4E-05
8. Installation of Insulation in Buildings (Residential)	0.00001	5.3E-06	0.00	0.0002	4.5E-08	0.00613	0.3	6.9E-07	5.3E-07
9. Service Life					6.1E-09			9.4E-08	7.2E-08
10. Demolition and Disposal of Insulation in Buildings									
11. Recycling of EPS Foam	0.003	4.3E-04	0.09	0.02	3.0E-07	1.68	62.0	4.5E-06	3.5E-06
12. Formulation of Coatings and solder					5.6E-03			8.6E-02	6.6E-02
13. Application of Coatings (Commercial)	0.743	3.6E-02	22.86	1.79	8.2E-04	46.5	3,390.0	1.3E-02	9.6E-03
13. Application of Coatings (Residential)	0.026	1.2E-03	0.79	0.05	1.4E-04	1.43	64.6	2.1E-03	1.6E-03
14. Use of Solder	0.00002	1.5E-04	0.01	0.01	4.8E-07	0.591	21.7	7.3E-06	5.6E-06
Generic based on Monitoring data (near facility)	0.1 to 10 ug/L					500 to 1,000 ug/g			10 to 500
Generic based on Monitoring data (not near facility)	0.0001 to 0.1 ug/L					30 to 500 ug/g			0.1 to 10 ug/g

1.1.6 1.1.7 Uncertainty and Variability in the Environmental Exposure Assessment

Concentrations of HBCD in environmental and biological media are expected to vary. Close proximity to facilities and other sources is likely to lead to elevated concentrations compared to locations that are more remote. A combination of monitoring data from the U.S. and international sources were used. When considering monitoring data from international sources, it is unknown whether those sampling sites are representative of sites within the U.S. When modeling HBCD, EPA/OPPT acknowledges the conservative nature of surface water models used.

1.2 1.2 Approach Used for Exposure Assessment to General Population and Highly Exposed Groups

Commented [WA1]: Three groups are called out here, however later in the text it refers to only general population and highly exposed groups. Based on reading the text it seems a separate "consumer" category was not considered

HBCD is used primarily as an additive flame retardant in a variety of materials. HBCD has been detected in the indoor and outdoor environment and in human biomonitoring, indicating that some amount of exposure is occurring in some individuals, although exposures likely vary across the general population. See Supplementary File for a summary of environmental and biomonitoring studies where HBCD has been detected.

Commented [WA2]: This sentence is very vague. It is unclear what the aim/main point of the sentence is.

The migration of additive flame retardants from indoor sources such as building materials, plastics, and other articles appears a likely source of flame retardants found in indoor dust, suspended particles, and indoor air [ADDIN EN.CITE ADDIN EN.CITE.DATA]. However, the relative contribution of different sources of HBCD in these matrices is not well characterized. For example, HBCD present in building insulation, textiles, and recycled XPS and EPS materials are likely to have differing magnitudes of emissions.

Emission of HBCD is likely to occur through the following mechanisms: diffusion from sources and gas-phase mass-transfer, abrasion of materials to form small particulates through routine use, and direct transfer from articles to dust adhered to the article surface. Releases of flame retardants to the outdoor

environment may occur through direct releases to water and air as well as indirect releases from the indoor environment.

The general population may be exposed to HBCD through oral, inhalation, or dermal exposure although oral exposure is the greatest contributor to overall exposure.

Receptors are categorized as general population and highly-exposed groups, similar to environmental exposure assessment. EPA/OPPT considered available monitoring data alongside modeled estimates to characterize exposures to the general population and highly-exposed groups. Estimates of exposure for highly-exposed groups likely apply to relatively fewer individuals, while the general population exposure estimates are expected to be relevant for more people in the general population.

Commented [WA3]: And consumers? See note above about the section title

The general population exposure group is more homogenous as this group is exposed to background-levels of HBCD in media. The highly-exposed group is more heterogenous in that it incorporates variable scenario-specific exposures from releases to water, air, and consumer articles. For all receptors, EPA estimated exposures using EPA exposure factors, some of which were recently updated (EPA 2017). EPA also considered estimated intakes and doses reported by others but acknowledges that these estimates were generally derived using different exposure factors. EPA acknowledges that some exposure factors for highly-exposed groups could be higher than the general population. This is further discussed in Appendix ZZ.

General population receptors are individuals who are not expected to live close to point sources and are not expected to have many, or any, HBCD products in their home, although data on the prevalence of articles containing HBCD in homes throughout the United States is not available. Exposure to these individuals is characterized using monitoring data. No modeling data is used for these receptors. The following pathways are considered:

Commented [WA4]: Not consistent with above statement where it says monitoring and modeled estimates were considered for both groups.

- Dietary (all foods- breast milk, fish/shellfish, meat/eggs/dairy, grain/vegetables/fruit)
- Dust and soil ingestion
- Inhalation of particles
- Dermal absorption of dust and soil

Highly-exposed group receptors are individuals who are expected to live close by point sources and/or may have HBCD insulation products in their homes and/or automotive components in their vehicles. Exposure to these individuals is supplemented by modeling and compared with monitoring data. Modeled dust and indoor air concentrations, modeled outdoor air concentrations, modeled water concentrations, and estimated soil, fish, dietary concentrations will be considered alongside available monitoring data. The following pathways are considered:

- Dietary (all foods- breast milk, fish/shellfish, meat/eggs/dairy, grain/vegetables/fruit), possible elevated concentrations based on modeled surface water, soil, sediment and trophic transfer bioconcentration (BCF) or bioaccumulation factor (BAF)
- Dust ingestion- indoor dust and air modeled using EPA's Indoor Environmental Concentrations in Buildings with Conditioned and Unconditioned Zones (IECCU)
- Dermal absorption of dust- same as above, but with consideration of modeled dust concentrations
- Inhalation of particles- outdoor air modeled using EPA's Integrated Indoor and Outdoor Air Calculator (IIOAC)

- Surface water modeling- modeled using PSC

Central tendency and high-end exposure factors are considered and provided for these types of receptor groups. EPA/OPPT reports age-specific doses for each overall receptor category and acknowledges that there could be further refinement of highly exposed and potentially exposed or susceptible subpopulations (PESS) within this overall schema. Further characterization of heterogeneity of who is included in the highly-exposed group and associated variability of exposure factors within the highly-exposed group is discussed in the Supplemental File. This supplementary document further describes qualitative and semi-quantitative examples of highly exposed and susceptible subpopulations within the highly exposed group.

Receptor Description	Exposure Descriptor	
	Central Tendency	High-End
General Population by Age Group	- Individuals not living near facilities - Uncertainty with source apportionment of indoor sources - Less exposure pathways - Central tendency exposure factors and concentrations - Overlaps more with general population, applies to the most people	- Individuals not living near facilities - Uncertainty with source apportionment of indoor sources - Less exposure Pathways - High-end exposure factors and concentrations - Overlaps more with general population, applies to more people
Highly Exposed Groups by Age	- Individuals who are living near facilities - Modeled HBCD insulation as source of indoor dust and air - More Exposure pathways - Central tendency exposure factors and concentrations - Overlaps more with PESS, these exposure estimates will be the high but will apply to fewer people	- Individuals who are living near facilities - Modeled HBCD insulation as source of indoor dust and air - More exposure pathways - High-end exposure factors and concentrations - Overlaps more with PESS, these exposure estimates will be the highest but will apply to the fewest number of people

Commented [WA5]: Most across all four? Highly-exposed-central tendency, highly-exposed high-end, gen pop-high end?

Commented [WA6]: Than which category? Than the central tendency gen-pop? Suggest adding detail to make it clear what this statement is comparing against.

Commented [WA7]: Suggest adding in parentheses what the additional exposure pathways are

Commented [WA8]: Same comment as above

Commented [WA9]: Same comment as above

Commented [WA10]: The rationale for why this text occurs here is buried until the end of the paragraph. Suggest a leading sentence stating that current trends indicate that exposures near facilities could approach general population exposures based on recent trends of reduced HBCD uses. Something along these lines.

It was unclear why this was here until the end. OR

Suggest adding a subheading here to acknowledge that this section discusses current trends in HBCD occurrence.

Recently, manufacturers of HBCD indicated that production of HBCD in the United States is being phased out [Reference]. Since the initiation of this risk evaluation period in December 2016, HBCD may still be imported into the United States and handled by processing facilities. However, the amount of HBCD and the intended uses of HBCD in the United States may be lower when compared to past

amounts and uses. Therefore, exposure potential in the future may be lower than the past. EPA/OPPT has included a discussion of observed trends in monitoring data and has noted observed trends with estimated releases to the environment. While both trends suggest reduced sources of HBCD in the environment, HBCD's persistence and long-range transport potential, coupled with extended shelf-life of HBCD containing articles in buildings and recycling of these same articles throughout the United States suggests that there may be a continuing pool of available HBCD extending into the future. EPA/OPPT notes that should sources emitted from industrial facilities continue to decline, over time exposures near these facilities could likely trend towards general population exposures.

EPA also considered age-specific differences in exposure. EPA used the CHAD database to inform how much time individuals spend in various microenvironments as described in Supplementary File [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>2009</Year><RecNum>235</RecNum><DisplayText>(U.S. EPA, 2009)</DisplayText><record><rec-number>235</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523618">235</key></foreign-keys><ref-type name="Web Page">12</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Consolidated Human Activity Database</title></titles><dates><year>2009</year></dates><work-type>Website</work-type><urls><related-urls><url>http://www.epa.gov/chadnet1/</url></related-urls></urls><modified-date>U.S. Environmental Protection Agency</modified-date></record></Cite></EndNote>]. EPA used the Exposure Factors Handbook to inform body weights and intake rates for children and adults also described in Supplementary File [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>2011</Year><RecNum>236</RecNum><DisplayText>(U.S. EPA, 2011)</DisplayText><record><rec-number>236</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523684">236</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Exposure factors handbook: 2011 edition (final)</title></titles><dates><year>2011</year></dates><pub-location>Washington, DC</pub-location><publisher>U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment</publisher><isbn>EPA/600/R-090/052F</isbn><work-type>EPA Report</work-type><urls><related-urls><url>http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=236252</url></related-urls></urls><language>English</language><modified-date>U.S. Environmental Protection Agency</modified-date></record></Cite></EndNote>]. [REF _Ref449618194 \h * MERGEFORMAT] provides an overview of exposure pathways considered for various age groups.

Commented [WA11]: Table 0.5 is out of place and it is not referenced in the text. Suggest moving it up to

Commented [WA12]: It would be helpful to go ahead and list the age groups in this paragraph.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: Summary of Exposure Pathway and Receptor Age Groups used in the Analysis

Exposure Pathway	Generic Near-Facility	General Population	Age Groups
Dietary: **Meats** **Dairy** **Fish and Shellfish** **Fruits** **Vegetables** **Grains** **Breast Milk** **Drinking water**	Monitoring values and modeled estimates.	Monitoring values	All age groups for all food types. Note, infants only for breast milk ingestion and individuals older than 1 for fish/shellfish ingestion.

Dust Ingestion	Monitoring values and modeled estimates from indoor sources.	Monitoring values	All age groups.
Soil Ingestion	Monitoring values and modeled estimates from outdoor sources.	Monitoring values	All age groups.
Dermal contact with Dust and Soil	Monitoring values and modeled estimates from indoor and outdoor sources.	Monitoring values	All age groups.
Inhalation of Suspended Particles	Monitoring values and modeled estimates from indoor and outdoor sources.	Monitoring values	All age groups.
Biomonitoring			All age groups

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: Summary of Exposure Pathway and Approach used in the Analysis

Commented [WA13]: Is this for both the gen pop and highly exposed groups?

Exposure Pathway	Direct Use of Reported Monitoring Data	Interpretation, Scaling of Reported Environmental Monitoring Data, Previously Completed Assessments	IECCU	IIOAC	Interpretation Scaling of Modeled Water or Soil Concentrations with BCF Values
Dietary: **Meats** **Dairy** **Fish and Shellfish** **Fruits** **Vegetables** **Grains** **Breast Milk** **Drinking water**	Yes	Yes			Yes
Dust Ingestion	Yes	Yes	Yes		
Soil Ingestion	Yes	Yes			
Dermal contact with Dust and Soil	Yes	Yes			
Inhalation of Suspended Particles		Yes	Yes	Yes	

1.2.1 1.2.1 Dietary Exposure

The exposure dose associated with ingesting food is generally derived by multiplying the concentration of chemical in food by the ingestion rate for that food and dividing by body weight [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>1992</Year><RecNum>237</RecNum><DisplayText>(U.S. EPA, 1992)</DisplayText><record><rec-number>237</rec-number><foreign-keys><key app="EN" db-

id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523739">237</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Guidelines for exposure assessment</title></titles><dates><year>1992</year></dates><pub-location>Washington, DC</pub-location><publisher>U.S. Environmental Protection Agency, Risk Assessment Forum</publisher><isbn>EPA/600/Z-92/001</isbn><urls><related-urls><url>http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=15263</url></related-urls></urls><modified-date>U.S. Environmental Protection Agency</modified-date></record></Cite></EndNote>]. Within this overall framework, exposures could be estimated by grouping all foods and liquids together and using a generic overall exposure factor, disaggregating discrete food groups and using food group specific exposure factors, or estimating exposures for unique food items. Available monitoring data was used to estimate central tendency and high-end concentration of HBCD in food groups. The concentration of HBCD in certain food groups can also be derived through combining monitored or modeled concentrations of HBCD in surface water and soil with BCFs [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>2007</Year><RecNum>231</RecNum><DisplayText>(U.S. EPA, 2007)</DisplayText><record><rec-number>231</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523433">231</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Exposure and fate assessment screening tool (E-FAST): Version 2.0, documentation manual</title></titles><dates><year>2007</year></dates><urls></urls></record></Cite></EndNote>]. [REF _Ref449618203 \h * MERGEFORMAT] shows how these general approaches were used to estimate generic near-facility and general population exposures from fish ingestion.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: Summary of Food and Fish Concentrations used in the Analysis

Approach	Highly Exposed Group	General Population
Monitored central tendency (CT) food group concentration		Yes
Monitored high-end (HE) food group concentration		Yes
Monitored central tendency surface water concentration (near point sources) and CT and HE BCF to estimate fish tissue concentration	Yes	
Modeled central tendency surface water concentration and CT and HE BCF to estimate fish tissue concentration	Yes	

Equations used to estimate exposure due to food ingestion exposures are presented below.

When monitored or modeled surface water concentrations are available:

$$ADD = \frac{SWC \times BCF \times IR \times CF1 \times CF2 \times ED}{BW \times AT} \qquad (4)$$

Where

ADD	=	Average daily dose due to fish ingestion (mg/kg-day)
SWC	=	Surface water concentration (µg/L)
BCF	=	Bioconcentration factor (L/kg)
IR	=	Fish ingestion rate (g/day)
$CF1$	=	Conversion factor for mg/µg

$CF2$ = Conversion factor for kg/g
ED = Exposure duration (year)
BW = Body weight (kg)
AT = Averaging time (year)

When food concentrations from monitoring data are available:

$$ADD = \frac{FC \times IR \times CF1 \times CF2 \times ED}{BW \times AT} \quad (5)$$

Where

ADD = Average daily dose due to food ingestion (mg/kg-day)

FC = Food concentration (µg/kg)

IR = Food ingestion rate (g/day)

$CF1$ = Conversion factor to mg/µg

$CF2$ = Conversion factor for kg/g
ED = Exposure duration (year)

BW = Body weight (kg)

AT = Averaging time (year)

[REF _Ref449618214 \h * MERGEFORMAT] presents all the values that were used in the food ingestion equations to estimate exposures. Additional detail on how these values were derived is available in Appendix xxx.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]. Summary of Inputs for Estimating Fish Ingestion Dose

Parameter	Central	High-End
Monitored fish concentration µg/mg		
Estimated fish concentration from monitored surface water and BCF (ug/mg)		
Estimated fish concentration from modeled surface water across all scenarios and BCF (ug/mg) Range (median)		
Monitored surface water concentration (ug/L)	0.01	0.0001
Modeled surface water concentration across all scenarios (ug/L) Range (median)		
BCF L/kg	4,650	6,531
Fish ingestion rate for adults - varies with age (see Supplementary File) grams per day	5	22

Commented [WA14]: Will these blank cells be filled in in a future draft?

Near-facility children are assumed to live near a facility with elevated concentrations of HBCD for the entire duration of that life stage. Near-facility adults are assumed to live near a facility with elevated concentrations of HBCD for a portion of their entire life, depending on whether it was high-end or a central tendency estimate. The upper-end estimate of residential mobility of 33 years was selected for a high-end exposure duration [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>2011</Year><RecNum>236</RecNum><DisplayText>(U.S. EPA, 2011)</DisplayText><record><rec-number>236</rec-number><foreign-keys><key app="EN" db-

Commented [WA15]: Adding a phrase to provide more specifics about the "portion"

id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523684">236</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Exposure factors handbook: 2011 edition (final)</title></titles><dates><year>2011</year></dates><pub-location>Washington, DC</pub-location><publisher>U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment</publisher><isbn>EPA/600/R-090/052F</isbn><work-type>EPA Report</work-type><urls><related-urls><url>http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=236252</url></related-urls></urls><language>English</language><modified-date>U.S. Environmental Protection Agency</modified-date></record></Cite></EndNote>]. A central tendency value of 13 years was also selected [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>2011</Year><RecNum>236</RecNum><DisplayText>(U.S. EPA, 2011)</DisplayText><record><rec-number>236</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523684">236</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Exposure factors handbook: 2011 edition (final)</title></titles><dates><year>2011</year></dates><pub-location>Washington, DC</pub-location><publisher>U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment</publisher><isbn>EPA/600/R-090/052F</isbn><work-type>EPA Report</work-type><urls><related-urls><url>http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=236252</url></related-urls></urls><language>English</language><modified-date>U.S. Environmental Protection Agency</modified-date></record></Cite></EndNote>]. For the other portion of their adult life, it was assumed that they were exposed to central tendency fish concentration values based on monitoring data.

The weight of evidence figures below shows the distribution of all fish monitoring in ug/mg ww.

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1]. HBCD Concentration in Fish (µg/mg lw)

Commented [WA16]: "ww" not "lw"?

Note, fish concentrations were reported in the literature on a lipid weight and wet weight basis. Species-specific lipid content as reported by the individual studies, was not collected. Lipid content in fish ranges from <1% to 15% (EPA 2011). To convert from lipid concentration to wet weight concentration, the following equation is used.

$$\boldsymbol{Conc, ww = Conc, lw} \times \frac{\boldsymbol{\%\, lipid}}{\boldsymbol{100\%}} \qquad \textbf{(3)}$$

Where

$Conc, ww$ = Concentration on a wet weight basis, µg/kg ww

$Conc, lw$ = Concentration on a wet weight basis, µg/kg lw

% *lipid* = Percentage of fish that is comprised of lipids

Assuming 10% lipid fate, fish concentrations reported in lipid weight were multiplied by 10% to convert into wet weight for use alongside fish intake rates that are also based on wet weight. Fish concentrations derived by multiplying surface water concentration and BCF are also in wet weight and were compared to available monitoring data. Uncertainties associated with estimating wet weight fish concentrations are further described in Section xx.

In addition to reviewing the weight of evidence across all studies, the following key studies provide additional information on HBCD levels in fish. [HYPERLINK \l "_ENREF_44" \o "Chen, 2011 #150"] noted temporal and spatial trends for HBCD concentrations in fish. In Hyco River samples collected in Virginia, the authors note an increase in HBCD concentrations in carp, catfish, redhorse sucker, gizzard shad, and flathead catfish. Across all samples, mean HBCD concentrations ranged from ND to 22 µg/kg lw in 1999-2002 samples and increased to 13 to 4,640 µg/kg lw. Assuming 10% lipid, this converts to 1.3e-6 µg/mg ww to 4.64e-4 µg/mg ww.

In addition, [HYPERLINK \l "_ENREF_44" \o "Chen, 2011 #150"] conducted a meta-analysis of their present study and seventeen other studies to see if near-facility concentrations in fish differed from fish samples collected further away from facilities. The authors report that concentrations in fish sampled near point sources were generally 1 to 2 orders of magnitude higher than fish located further away from sources. [HYPERLINK \l "_ENREF_44" \o "Chen, 2011 #150"] reported fish concentrations near point sources ranging from 38 to 6,660 µg/kg lw (3.8e-6 to 6.6e-4 µg/mg ww) and concentrations in fish from more remote areas ranging from 0.1 to 51.5 µg/kg lw (1.0e-8 to 5.2e-6 µg/mg lw). [HYPERLINK \l "_ENREF_103" \o "Larsen, 2005 #179"] reported total HBCD concentrations ranging from ND to 73.9 µg/kg in various fish species collected in 2003 from the Chesapeake Bay (detection in 50 of 52 samples).

[HYPERLINK \l "_ENREF_10" \o "Allchin, 2003 #145"] reported HBCD concentrations in eel and trout from eight sampling locations along industrialized rivers in the UK. HBCD concentrations in eel ranged from 3.9e-5 to 1.0e-2 µg/mg ww, with average values ranging from 3.4e-4 to 4.7e-4 µg/mg ww. HBCD concentrations in trout ranged from <1.2e-6 µg/mg ww to 6.8e-3 µg/mg ww, with average values ranging from 2.0e-5 to 2.3e-3 µg/mg ww.

Table [STYLEREF 1 \s].X. Summary of Monitoring Data for HBCD Concentration in Fish Tissue

	Fish Concentration (µg/mg) ww
Range of all monitoring data	1e-9 to 1.6e-2
Range of central tendency monitoring data	1.2e-8 to 1.1e-3 (3.5e-6)
Range (central tendency) of key studies away from point sources) **A) [HYPERLINK \l "_ENREF_44" \o "Chen, 2011 #150"]** **B) [HYPERLINK \l "_ENREF_118" \o "Larsen, 2005 #179"]**	A) 1.0e-8 to 5.2e-6 B) ND to 7.4e-6
Range (central tendency) of key studies near point sources A) **[HYPERLINK \l "_ENREF_44" \o "Chen, 2011 #150"]** **C) [HYPERLINK \l "_ENREF_10" \o "Allchin, 2003 #145"]**	A) 3.8e-6 to 6.6e-4 C) <1.2e-6 to 6.8e-3 (2.0e-5 to 2.3e-3) 3.9e-5 to 1.0e-2 (3.4e-4 to 4.7e-4)

Commented [WA17]: Content?

Commented [WA18]: Once draft more final, a search and replace should be performed to ensure all references of "ug" are "µg"

Commented [WA19]: lw or ww?

Commented [WA20]: This sentence does not make sense, as there is a parentheses mid sentence that is not concluded. I've made edits that I think are appropriate, but it should be checked.

There are approximately 30 studies reporting HBCD concentrations in breast milk. Within those studies there is a wide range of concentrations, although there is general concordance across studies at central tendency. There were three key studies that provide a reasonable cross-section of available data sources.

Commented [WA21]: Suggest adding section headers to transition between mediums

The highest concentrations were observed by [HYPERLINK \l "_ENREF_52" \o "Eljarrat, 2009 #23"], in which HBCD was measured in milk samples collected from women in Spain, ranging from ND to 188 µg/kg lw, with an average of 47 µg/kg lw and a median of 27 ug/kg lw. Another large study by [HYPERLINK \l "_ENREF_65" \o "Eggesbo, 2011 #21"], collected milk samples from 193 mothers as part of the Norwegian Human Milk Study. HBCD levels in breast milk ranged from 0.1 to 31 ug/kg lw, with an average of 1.1 ug/kg lw. In the United States, [HYPERLINK \l "_ENREF_41" \o "Carignan, 2012 #108"] measured HBCD in the breast milk of 43 mothers. HBCD was detected in all samples with concentrations ranging from 0.36 to 8.1 ug/kg lw, with a geometric mean of 1.02 ug/kg lw.

Commented [WA22]: This means that Eljarrat et al. was also a large study, suggest adding the # of women included in that study in the preceding sentence.

Table [STYLEREF 1 \s].X. Summary of Monitoring Data for HBCD Concentration in Breast Milk

	Breast Milk Concentration µg/g (ug/kg)
Range of all monitoring data	ND to 0.188 (ND to 188)
Range of central tendency monitoring data	1.9E-4 to 2.7E-2 (0.19 to 47)
Range (central tendency) of key studies **A) [HYPERLINK \l "_ENREF_65" \o "Eggesbo, 2011 #21"]** **B) [HYPERLINK \l "_ENREF_41" \o "Carignan, 2012 #108"]** **C) [HYPERLINK \l "_ENREF_66" \o "Eljarrat, 2009 #23"]**	A) 0.1 to 31 (1.1) B) 0.36 to 8.1 (1.02) C) ND to 188 (47, 27)

The equation used to estimate exposure from ingestion of breastmilk is below.

$$ADD = \frac{BMC \times BMR}{BW} \qquad (9)$$

Where

ADD = Average daily dose due to ingestion of breastmilk (mg/kg-day)

BMC = Chemical concentration in breastmilk lipids (mg/g)

BMR = Breastmilk lipid ingestion rate (g/day)

BW = Body weight of infants (kg)

Parameters and data sources used as inputs into this equation are provided in the table below. Additional detail is provided in Appendix xx.

Table [STYLEREF 1 \s].X. Central tendency and high-end estimates used in breast milk exposure calculations

Parameter	**Central**	**High-End**
Breast Milk Concentration ug/g (ug/kg) lipid	0.001 (1)	0.05 (50)
Ingestion Rate of breast milk lipid (mg/L)	26	41.5

EPA considered ingestion of drinking water but did not quantify those concentrations in this risk evaluation. The concentration of HBCD in surface water is generally low and monitored levels of HBCD in drinking water are unavailable. Other assessments have included drinking water as a pathway and noted that expected exposures are quite low. The following exposure pathways are possible:

1. Ingestion of finished water at the tap, expected HBCD levels are low.
2. Ingestion of surface water, including suspended sediment, during recreation in lakes and rivers. HBCD levels are likely to be slightly more elevated than drinking water but intake rates and frequency of exposure are lower.
3. Ingestion of settled sediment during recreation in lakes and rivers, HBCD levels are more elevated.

The first pathway was incorporated using low surface water concentrations of 1e-6 ug/L as a surrogate for drinking water concentrations. Consideration of this exposure pathway or exclusion of this pathway has a small effect on total exposure. A qualitative discussion of other exposure pathways arising for scenarios such as those for PESS populations including tribal populations is included in the Supplementary File.

Commented [WA23]: Than suspended sediments in drinking water?

Commented [WA24]: Once draft is more final, a consistency check should be done so that "e" is always lowercase throughout document

1.2.2 1.2.2 Dust and Soil Ingestion

The exposure dose associated with incidentally ingested dust and soil is generally derived by multiplying the chemical concentration in dust or soil by the empirically derived ingestion rate of dust or soil and dividing by body weight [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>1992</Year><RecNum>237</RecNum><DisplayText>(U.S. EPA, 1992)</DisplayText><record><rec-number>237</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523739">237</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Guidelines for exposure assessment</title></titles><dates><year>1992</year></dates><pub-location>Washington, DC</pub-location><publisher>U.S. Environmental Protection Agency, Risk Assessment Forum</publisher><isbn>EPA/600/Z-92/001</isbn><urls><related-urls><url>http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=15263</url></related-urls></urls><modified-date>U.S. Environmental Protection Agency</modified-date></record></Cite></EndNote>]. The ingestion rate can be derived through tracer methods which measure tracer chemicals present both in soil and dust and in the urine and feces of humans and through biokinetic methods that use biomonitoring data and physiologically based pharmacokinetic (PBPK) models to back-calculate ingestion rates. An activity-pattern based method models hand-to-mouth and object-to-mouth contact to derive transfer rates of soil and dust to the mouth to estimate ingestion rate [ADDIN EN.CITE <EndNote><Cite><Author>Moya</Author><Year>2014</Year><RecNum>240</RecNum><DisplayText>(Moya and Phillips, 2014)</DisplayText><record><rec-number>240</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459524118">240</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Moya, J.</author><author>Phillips, L.</author></authors></contributors><auth-address>U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, Pennsylvania Avenue NW, Washington, DC, USA.</auth-address><titles><title>A review of soil and dust ingestion studies for children</title><secondary-title>J Expo Sci Environ Epidemiol</secondary-title></titles><periodical><full-title>J Expo Sci Environ Epidemiol</full-title></periodical><pages>545-54</pages><volume>24</volume><number>6</number><keywords><keyword>Adolescent</keyword

><keyword>Biomarkers/blood/urine</keyword><keyword>Child</keyword><keyword>*Child Behavior</keyword><keyword>Child, Preschool</keyword><keyword>*Dust</keyword><keyword>*Eating</keyword><keyword>Environmental Exposure/*analysis</keyword><keyword>Environmental Monitoring/methods</keyword><keyword>Humans</keyword><keyword>Infant</keyword><keyword>Pica</keyword><keyword>*Soil</keyword></keywords><dates><year>2014</year><pub-dates><date>Nov</date></pub-dates></dates><isbn>1559-064X (Electronic)
1559-0631 (Linking)</isbn><accession-num>24691008</accession-num><urls><related-urls><url>http://www.ncbi.nlm.nih.gov/pubmed/24691008</url></related-urls></urls><electronic-resource-num>10.1038/jes.2014.17</electronic-resource-num></record></Cite></EndNote>]. Estimated ingestion rates based on the activity-pattern method are informed by empirically and estimated variables [ADDIN EN.CITE <EndNote><Cite><Author>Ozkaynak</Author><Year>2011</Year><RecNum>241</RecNum><DisplayText>(Ozkaynak et al., 2011)</DisplayText><record><rec-number>241</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459524139">241</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Ozkaynak, H.</author><author>Xue, J.</author><author>Zartarian, V. G.</author><author>Glen, G.</author><author>Smith, L.</author></authors></contributors><auth-address>U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Research Triangle Park, NC, USA. ozkaynak.haluk@epa.gov</auth-address><titles><title>Modeled estimates of soil and dust ingestion rates for children</title><secondary-title>Risk Anal</secondary-title></titles><periodical><full-title>Risk Anal</full-title></periodical><pages>592-608</pages><volume>31</volume><number>4</number><keywords><keyword>Child</keyword><keyword>Child, Preschool</keyword><keyword>*Dust</keyword><keyword>*Environmental Exposure</keyword><keyword>Humans</keyword><keyword>Models, Theoretical</keyword><keyword>Risk Assessment</keyword><keyword>*Soil</keyword></keywords><dates><year>2011</year><pub-dates><date>Apr</date></pub-dates></dates><isbn>1539-6924 (Electronic)
0272-4332 (Linking)</isbn><accession-num>21039709</accession-num><urls><related-urls><url>http://www.ncbi.nlm.nih.gov/pubmed/21039709</url></related-urls></urls><electronic-resource-num>10.1111/j.1539-6924.2010.01524.x</electronic-resource-num></record></Cite></EndNote>] including:

- Hand and object-to-mouth frequency indoors and outdoors,
- Dust loading,
- Object: floor dust loading ratio,
- Soil skin adherence rate,
- Skin/soil surface contact rate,
- Maximum dermal loading of soil loading on hands,
- Surface-to-hand dust transfer efficiency,
- Hand and object-to-mouth transfer efficiency,
- Area of object mouthed and fraction of hand mouthed/event, and
- Bath and hand wash removal efficiency and frequency.

Chemical concentrations in dust or soil are required for the tracer and biokinetic methods. Loadings of a chemical in dust or soil are required for the activity-pattern method. The chemical concentration in dust or soil is defined as the mass of chemical present per mass of dust or soil. The chemical loading in dust is defined as the mass of chemical per surface area.

These terms are all related, but often only one of the three is reported in monitoring studies. If the surface area units are the same for loadings, the chemical dust loading divided by the total dust loading is equal to the chemical concentration. However, dust loadings of overall dustiness can also vary substantially by building or within a building. If paired chemical dust loading and chemical concentration data are available, an empirical relationship can be used to derive a relationship and conversion equation.

When an activity pattern method is used an overall dust or soil factor (units surface area/time) that incorporates variability from the bulleted list above can be used to estimate intake.

Equations used to estimate soil and dust ingestion are reported below. Note, this HBCD assessment uses Equation 6, while future assessments may use Equations 6 and/or 7 depending on data availability.

$$ADD = \frac{DC \times IR \times FD \times CF1 \times ED}{BW \times AT} \quad (6)$$

Where

ADD	=	Average daily dose due to soil or dust ingestion (mg/kg-day)
DC	=	Dust or soil concentration (µg/g)
IR	=	Dust or soil ingestion rate (g/day)
$CF1$	=	Conversion factor for mg/µg
FD	=	Fraction of day spent (dust ingestion only) in indoor microenvironment (unitless)
ED	=	Exposure duration (soil only-considers near facility time 13 and 33 years) (years)
BW	=	Body weight (kg)
AT	=	Averaging time (years)

$$ADD = \frac{DL \times DF \times TA \times ED}{BW \times AT} \quad (7)$$

Where

ADD	=	Average daily dose due to soil or dust ingestion (mg/kg-day)
DL	=	Dust or soil loading (µg/cm^2)
DF	=	Dust or soil factor (cm^2/ µg * mg/hr)
TA	=	Time spent in different microenvironments (hr/day), total should equal time awake
ED	=	Exposure duration (years)
BW	=	Body weight (kg)
AT	=	Averaging time (years)

Commented [WA25]: Should this be cm^2-mg/ug-hr?

A wide range of studies have reported HBCD concentrations in dust in a variety of indoor environments. No studies identified HBCD loadings in dust. Therefore, empirically-derived ingestion rates based on the tracer and biokinetic approaches as reported in the 2017 update of Chapter Five of the U.S. EPA Exposure Factors Handbook were used for this assessment.

The dust sampling locations were identified for each monitoring study and grouped into a microenvironment classification: residential, public and commercial building, automobile, and outdoors. The time spent by children and adults in each of these microenvironments was estimated for three generic activity-pattern profiles informed by EPA's Consolidated Human Activity Patterns Database [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>2009</Year><RecNum>235</RecNum><DisplayText>(U.S. EPA, 2009)</DisplayText><record><rec-number>235</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523618">235</key></foreign-keys><ref-type name="Web Page">12</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Consolidated Human Activity Database</title></titles><dates><year>2009</year></dates><work-type>Website</work-type><urls><related-urls><url>http://www.epa.gov/chadnet1/</url></related-urls></urls><modified-date>U.S. Environmental Protection Agency</modified-date></record></Cite></EndNote>]. The hours spent in each microenvironment were used to derive a fraction of the day that an individual was exposed to the selected HBCD concentrations in each microenvironment.

The table below presents all values that were used in equation 6 to estimate exposures from dust and soil ingestion. Additional detail on how these values were derived is available in Appendix xxx.

Table [STYLEREF 1 \s].X. Central tendency and high-end estimates used in dust and soil exposure calculations

Parameter	Central	High-End
Monitored dust concentration, residence ug/mg (ug/kg)	0.0005 (500)	0.005 (5,000)
Monitored dust concentration, P&CB ug/mg (ug/kg)	0.005 (5,000)	0.05 (50,000)
Monitored dust concentration, automobile ug/mg (ug/kg)	0.05 (50,000)	0.5 (500,000)
Monitored soil concentration, near facility ug/mg (ug/kg)	0.00005 (50)	0.0005 (500)
Monitored soil concentration, general population ug/mg (ug/kg)	0.000005 (5)	0.00003 (30)
Dust ingestion rate for toddlers[a] (mg/day)	60	100
Soil Ingestion Rate for toddlers[a] (mg/day)	50	120

[a]varies by age, see Appendix X for other ages

Commented [WA26]: ?

[HYPERLINK \l "_ENREF_47" \o "Dodson, 2012 #109"] measured flame retardants in house dust samples collected in 16 California homes in 2006 and 2011. Total HBCD was detected in 100% of the dust samples and ranged from 82 to 6,800 µg/kg (median = 190 µg/kg) in 2006 and from 39 to 1,800 µg/kg (median = 160 µg/kg) in 2011. [HYPERLINK \l "_ENREF_163" \o "Shoeib, 2012 #124"] measured flame retardants in house dust samples collected from homes located in Vancouver, Canada, between 2007 and 2008. Total HBCD was detected in all samples (n = 116) with concentrations that ranged from 20 to 4,700 µg/kg (mean = 450 µg/kg; median = 270 µg/kg). [HYPERLINK \l "_ENREF_4" \o "Abdallah, 2008b #11"] reported dust concentration across home, office, car, and public microenvironments. HBCD was detected in all 97 samples. Levels in homes ranged from 140 to 140,000 ug/kg, offices from 90 to 6,600 ug/kg, cars from 190 to 69,000 ug/kg, and public microenvironments from 2,300 to 3,200

ug/kg. [HYPERLINK \l "_ENREF_91" \o "Harrad, 2010 #284"] measured dust in daycares and schools in the UK. HBCD was detected in all 43 samples and ranged from 72 to 89,000 ug/kg. 95th percentile levels were reported at 37,000 ug/kg and average levels were 8,900 ug/kg. [HYPERLINK \l "_ENREF_11" \o "Allen, 2013 #103"] collected dust samples within airplanes. 40 dust samples were collected between November and December of 2010 from carpeted floors and low-lying air return vents on the walls of 19 commercial airplanes. Total HBCD was detected in 100% of the dust samples and ranged from 180 to 1,100,000 µg/kg. Central tendency estimates were 7,600 µg/kg in floor samples and 10,000 µg/kg in vent samples.

Commented [WA27]: Suggest putting this in a table, it will be more digestible.

Studies measuring the concentration of HBCD in soil are limited, with most studies measuring samples located near industrial facilities. [HYPERLINK \l "_ENREF_125" \o "Li, 2012 #41"], reported a statistically significant negative correlation between HBCD soil concentrations and distance from facility, noting a distance of 4 kilometers. The majority of soil sampling has been performed in Asia, most notably in China. [HYPERLINK \l "_ENREF_125" \o "Li, 2012 #41"] reported soil concentrations ranging from 0.88 to 6,901, which are likely more applicable to near-facility locations. Note that the 0.88 ug/kg sample was taken at a control site not located near facilities. The next highest concentration reported was 2,295 and the geometric mean across all samples was 83 ug/kg. [HYPERLINK \l "_ENREF_146" \o "Tang, 2014 #7"] collected samples in waste dump sites, industrial areas, and traffic areas with concentrations that ranged from 6 to 106 µg/kg. Soil concentrations near point sources have been reported as high as 89,000 ug/kg [ADDIN EN.CITE <EndNote><Cite><Author>EC</Author><Year>2008</Year><RecNum>226</RecNum><DisplayText>(EC, 2008)</DisplayText><record><rec-number>226</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459521865">226</key></foreign-keys><ref-type name="Report">27</ref-type><contributors><authors><author>EC,</author></authors></contributors><titles><title>Risk assessment: Hexabromocyclododecane</title></titles><dates><year>2008</year></dates><pub-location>Luxembourg</pub-location><publisher>European Commission</publisher><isbn>R044_0805_env_hh_final_ECB</isbn><urls><related-urls><url>http://echa.europa.eu/documents/10162/661bff17-dc0a-4475-9758-40bdd6198f82</url></related-urls></urls></record></Cite></EndNote>]. The sample depth and proximity to source influence soil concentrations.

Commented [WA28]: Unclear what this statement means

Commented [WA29]: Suggest only reporting the near-facility sites and then reporting that they also took a sample at a control site that measured 0.88 ug/kg

Commented [WA30]: In Asia? Or overall? This paragraph focuses on results from Asia, so it is unclear if this refers to outside Asia

[HYPERLINK \l "_ENREF_146" \o "Tang, 2014 #7"] collected 90 samples across the Ningbo Region of China that are more likely applicable to the general population. Samples collected in residential and agricultural areas ranged from ND to 46 µg/kg.

Table [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1]. Summary of HBCD dust and soil monitoring values (µg/mg)

	Dust Concentration (µg/kg)	Soil Concentration (µg/kg)
	Dust Concentration (µg/kg)	Soil Concentration (µg/kg)
Range of all Monitoring Data	TBD	TBD
Range of central tendency Monitoring Data	TBD	TBD
Range (central tendency) of key studies (Residence for Dust, away from point sources for soil) A) Dodson et al. (2012 **B) [HYPERLINK \l "_ENREF_163" \o "Shoeib, 2012 #124"]** **C) [HYPERLINK \l "_ENREF_4" \o "Abdallah, 2008b #11"]** **D) [HYPERLINK \l "_ENREF_200" \o "Tang, 2014 #253"]**	TBD	D) ND – 46
Range (central tendency) of key studies (P&CB, Auto for Dust, near point sources for soil) **C) [HYPERLINK \l "_ENREF_4" \o "Abdallah, 2008b #11"]** **E) [HYPERLINK \l "_ENREF_91" \o "Harrad, 2010 #284"]** F) Allen et al. (2013 **G) [HYPERLINK \l "_ENREF_125" \o "Li, 2012 #41"]** **H) [HYPERLINK \l "_ENREF_200" \o "Tang, 2014 #253"]**	TBD	G) 0.88 – 6,901 H) 6 -106

1.2.3 1.2.3 Dermal Exposures to Dust, Soil, and from Materials

EPA estimated the loading expected to present on skin through contact with dust, soil, and materials containing HBCD throughout the day. Two approaches were used to estimate this loading. The first was based on hand-wipe samples. The second was based on measured dust and soil concentrations and age-specific adherence factors. After estimating the loading, an absorbed fraction of 6.5% was applied based on data reported by xxx.

1.2.4 1.2.4 Consumer Exposures during Use of HBCD in EPS/XPS Insulation in Residences and Auto Components

In order to estimate the presence and fate of HBCD in vapor phase, settled dust, airborne particulate matter, and interior surfaces, a series of simulations were conducted for a "typical" residential building and a "typical" passenger vehicle by using existing mass transfer models and simulation tools. Most parameters were either obtained from data in the literature or estimated with empirical and QSAR models. All the simulations were conducted with IECCU version 1.1 (EPA 2017).

The modeling results were compared with limited experimental data. The predicted HBCD concentrations in settled dust in the living space were in line with the field measurements. Additionally, the predicted temperature dependence of the HBCD emission rate is in good agreement with the laboratory testing results reported by the Japanese researchers.

EPA/OPPT used the following general mass balance equation as defined in the user guide of the IECCU model to estimate the indoor concentrations of HBCD in indoor air and dust of a multi-zone indoor environment (Bevington et al., 2017).

$$V_i \frac{dC_i}{dt} = \sum_{j=1}^{n_1} A_j E_j - \sum_{k=0}^{n_2} Q_{ik} C_i + \sum_{k=0}^{n_3} Q_{ki} C_k - \sum_{m=1}^{n_4} S_m - \sum_{p=1}^{n_5} P_p - \sum_{q=1}^{n_6} D_q \quad (1)$$

where V_i is volume of zone i (m^3)

C_i is air concentration in zone i ($\mu g/m^3$)

t is elapsed time (h)

A_j is area of source j in zone i (m^2)

E_j is emission factor for source j in zone i ($\mu g/m^2/h$)

Q_{ik} is air flow from zone i to zone k, $i \neq k$ (m^3/h)

Q_{ki} is air flow from zone k to zone i, $k \neq i$ (m^3/h)

C_k is air concentration in zone k ($\mu g/m^3$)

S_m is sorption rate onto interior surface m in zone i ($\mu g/h$)

P_p is rate of sorption by airborne particulate matter p in zone i ($\mu g/h$)

D_q is rate of sorption by settled dust q in zone i ($\mu g/h$)

Subscripts j, k, l, m, p, and q are summation counters

n_1 through n_6 are item numbers for their respective summations.

Equation 1 states that the change of the concentration in air in zone i is determined by six factors: (1) the emissions from the sources in the zone, (2) the rate of chemical removed from zone i by the ventilation and interzonal air flows (Q_{ik}), (3) the rate of chemical carried into zone i by the infiltration and interzonal air flows (Q_{ki}), (4) the rate of chemical sorption by interior surfaces, (5) the rate of chemical sorption by airborne particles, and (6) the rate of chemical sorption by settled dust. Given a set of initial conditions, Equation 1 can be solved numerically.

Equation 1 does not include the term for chemical reactions because HBCD is chemically inert at normal temperatures. Also note that the air concentrations in Equation 1 — C_i and C_k — can be used to represent either the gas-phase or particle-phase concentrations or both.

Emissions from the source

The emissions of HBCD from polystyrene insulation materials were modeled by the modified state-space (MSS) method (Guo, 2013; Bevington et al., 2017), which divides the source into a finite number of "slices" parallel to the exposed surface. The mass transfer rate from the material surface to bulk air is given by Equation 2:

$$R = A E = A H_a \left(\frac{C_m}{K} - C_a \right) \quad (2)$$

where

R is emission rate, µg/h,

E is emission factor, µg/m^2/h,

A is the exposed surface area of the source, m^2,

H_a is the overall gas-phase mass transfer coefficient, m/h, calculated from Equation 3,

C_m is the concentration of chemical in the surface layer of material, µg/m^3,

C_a is the concentration of chemical in bulk air, µg/m^3,

K is the material-air partition coefficient, dimensionless.

$$\frac{1}{H_a} = \frac{1}{K\,h_m} + \frac{1}{h_a} \qquad (3)$$

where h_m and h_a are, respectively, solid and gas-phase mass transfer coefficients, m/h.

Several models are available for calculating the gas-phase mass transfer coefficient. In this work, EPA/OPPT used the method based on Sherwood number (Bennet & Myers, 1982), which is accessible in EPA's program PARAMS 1.1 (EPA 2005). The solid-phase mass transfer coefficient can be calculated from Equation 4:

$$h_m = \frac{D_m}{\Delta L} \qquad (4)$$

where D_m is the solid-phase diffusion coefficient, m^2/h, and ΔL is the travel distance between two adjacent slices, m.

Thus, the key parameters for modeling emissions from solid materials are the initial content of chemical in the solid material (C_m at time=0), the material/air partition coefficient (K), and the solid-phase diffusion coefficient (D_m). Other parameters — the initial concentration in air (usually C_a=0 at time=0), gas-phase mass transfer coefficient (h_a), solid-phase mass transfer coefficient (h_m), and the thickness of the source (for determining ΔL) — are easy to obtain.

Sorption by interior surfaces

The sorption of airborne chemical by interior surfaces plays an important role in determining the air concentrations for SVOCs. It has a minimal effect on very volatile organic compounds (VVOCs) and VOCs. In this model, the sorption by interior surfaces is represented by the same mass transfer equations for the source (i.e., Equations 1 through 4). The only difference between a source and a sink is the direction of the mass transfer. In the presence of sources, the interior surfaces act as a sink of airborne chemicals; when the sources diminish or are removed, the surfaces may become a secondary source by re-emitting the chemical into indoor air. Thus, the mass transfer between air sources and sinks can go either direction.

Sorption by airborne particulate matter

In this model EPA/OPPT assumes that there is an instantaneous equilibrium between the SVOC concentration in air and that in the particle phase (Xu & Little, 2006; Liu et al., 2013). In general, this assumption is valid if neither the particle-air partition coefficient (K_p) nor the particle diameter is very large. Typically, K_p should be no greater than 10^8 (Guo, 2014b), which is the case for HBCD in insulation materials.

Airborne particle can deposit on interior surfaces resulting in reduced mass concentration in indoor air. This factor is considered in the model (Equation 5 or, equivalently, 6),

$$R_d = S\, v_d\, C_p \quad (5)$$

$$R_d = V\, k_d\, C_p \quad (6)$$

where

R_d is the deposition rate, number/h

S is the area of interior surfaces, m^2

v_d is the deposition velocity, m/h

C_p is the particle concentration in air, number/m^3

V is the volume of the zone, m^3

k_d is the first-order deposition rate constant, h^{-1}.

Sorption by settled dust

The instantaneous equilibrium assumption for airborne particles is not applicable to settled dust because the average size of the latter is usually much larger than the former. Thus, the equilibrium assumption may result in overestimation of HBCD concentration in dust. The mass transfer between the gas phase and dust particles is modeled by the MSS method (Equations 2 to 4). The difference between the source and dust particle is that the areas of the "slices" are all the same for source materials whereas the dust particle is divided into a finite number of concentric hollow spheres with difference contact areas. See Guo (2014a) for details.

Simulation results — (1) HBCD in a "typical" home

Details of parameter estimation are discussed in Section 2.5 of this document. Simulation results are presented in Figures 1 through 5. As shown in Figure 3, the predicted HBCD content in house dust is in line with the measured values in the literature. Table 1 presents the mass balance results at the 100 elapsed days.

Commented [ZG31]: It is **Section 2.6** in the draft supplementary document.

The predicted emission rates (Figure 4), sorption rates (Figure 5) and the mass balance (Table 1) were also obtained with IECCU.

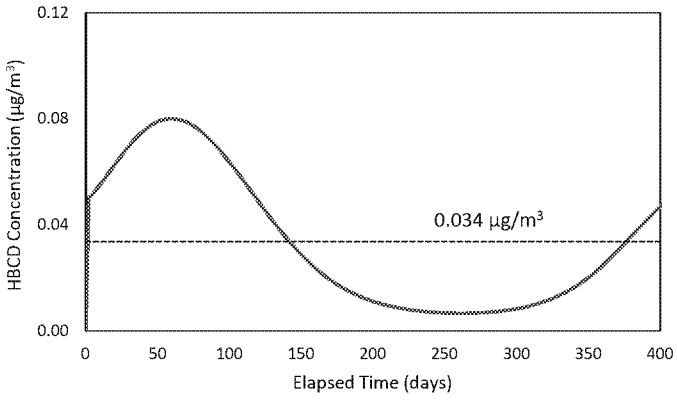


Figure 1. Predicted gas-phase HBCD concentration in living area. The simulation start date was the 1th of May. Emissions are stronger in summer than in winter.

Commented [ZG32]: I changed the y-axis label from "HBCD Content" to "HBCD Concentration".

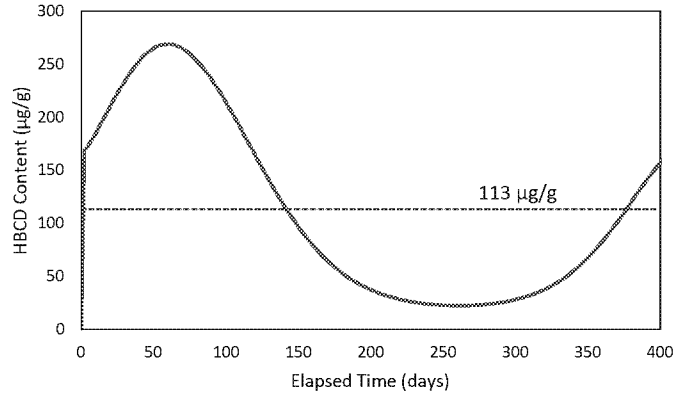


Figure 2. Predicted HBCD concentration in airborne PM in living area.

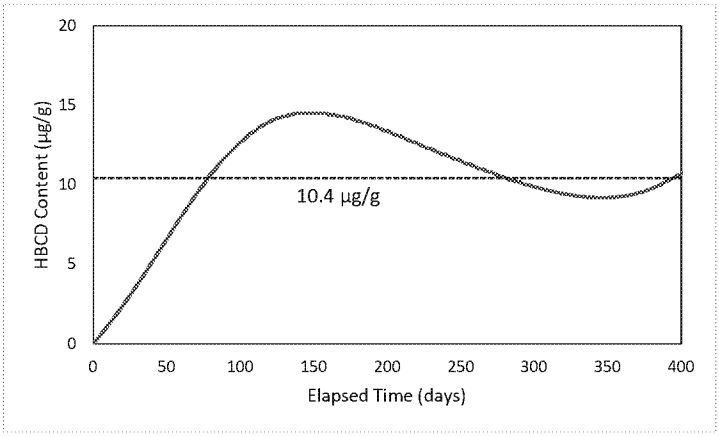


Figure 3. Predicted HBCD concentration in settled dust.

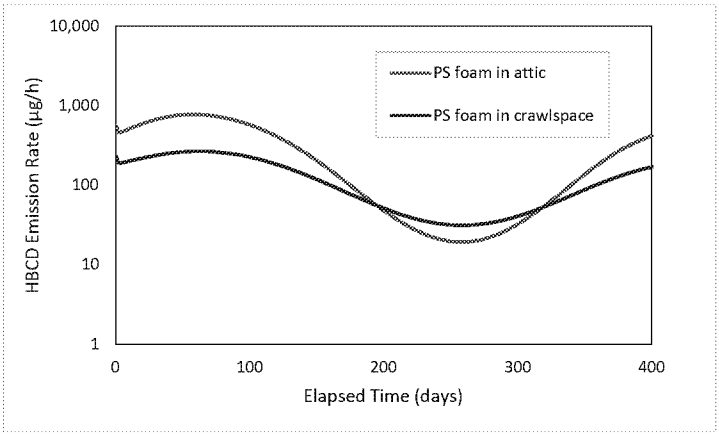


Figure 4. Predicted HBCD emission rates from polystyrene foam boards in attic and crawlspace.

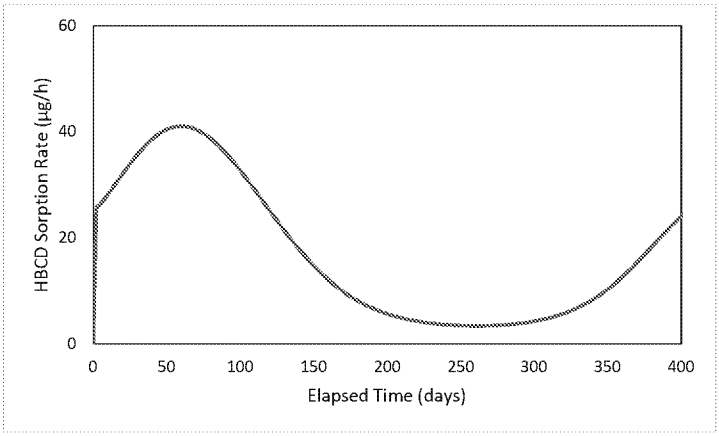


Figure 5. Rate of HBCD sorption by gypsum board walls.

Table 1. Mass balance results for HBCD in the simulated home at 100 elapsed days.

Emission/Fate		Mass (µg)	Percentage of emitted (%)
Total HBCD Emitted		2.18×10^{6}	
HBCD Fate	Vented out	$2.06E\times10^{6}$	94.3%
	Remaining in air	4.94×10^{2}	0.02%
	Absorbed by sinks	$8.65E\times10^{4}$	4.0%
	PM deposition	$7.84E\times10^{3}$	0.4%
	In dust	$8.13E\times10^{3}$	0.4%
	Total	$2.18E\times10^{6}$	100%

Simulation results — (2) HBCD in passenger vehicles

Simulation results

The HBCD concentrations inside the cabin are shown in Figure 6 and the concentrations in the settled dust in Figure 7. Note that we have assumed that all the dust particles are freshly introduced and the initial HBCD concentration in the dust is zero, and that the vehicle is new (Thus, the emission rate decreases over time and then become steady).

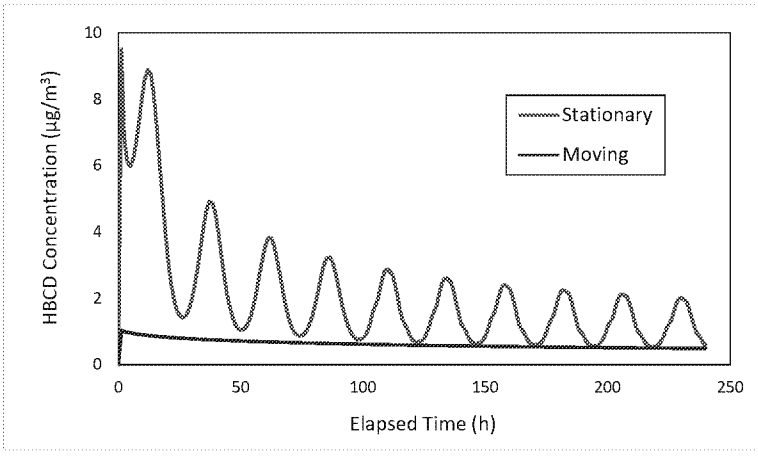
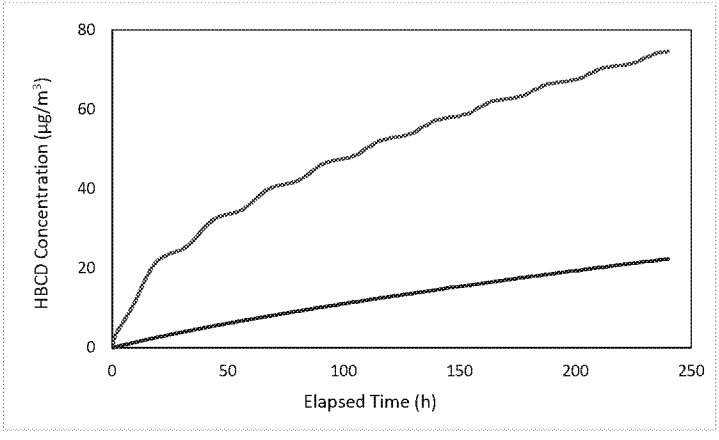


Figure 6. Predicted HBCD concentrations in vehicle's cabin.



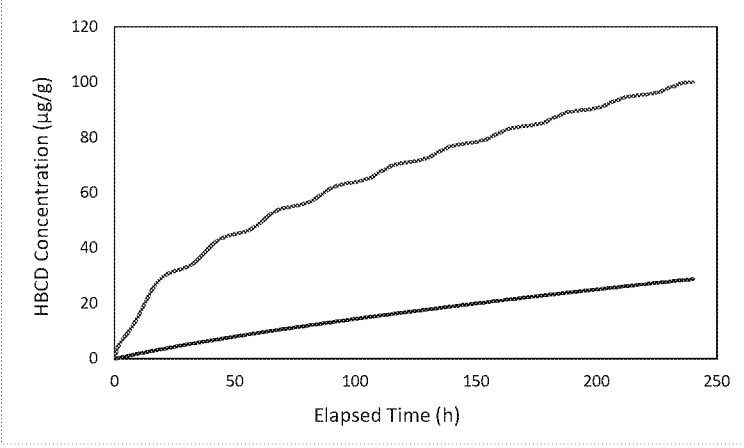


Figure 7. Predicted HBCD concentrations in the settled dust in vehicle's cabin. The dust contained no HBCD initially.

Discussion

XPS versus EPS foam boards

Extruded polystyrene (XPS) insulation is manufactured through an extrusion process, which produces a closed-cell rigid insulation. In contrast, expanded polystyrene (EPS) insulation is manufactured by using a mold to contain small foam beads. Heat or steam is then applied to the mold, which causes the small beads to expand and fuse together. This manufacturing process produces open-cell insulation (see [HYPERLINK "https://www.kingspan.com/meati/en-in/product-groups/insulation/knowledge-base/faqs/general/what-is-the-difference-between-xps-and-eps"]).

The presence of interconnected voids in the EPS foam facilitates both heat and mass transfers in the foam. According to website [HYPERLINK "http://www.giasxps.ro/index.php/en/electronic-library-polystyrene/77-xps-eps-comparison"], the resistances to water vapor diffusion are as follows:

Air = 1

EPS = 50 — 70

XPS = 50 — 250

These numbers suggest that the solid-phase diffusion coefficient for the low-performance XPS foam is about the same as that for the EPS foam and that the diffusion coefficient for the high-performance XPS foam can be as small as one fourth to one fifth of that for the EPS foam.

In the Huang et al. (2017) paper, the XPS and EPS foams are lumped into a single material type. To evaluate the difference in HBCD emissions between XPS and EPS, EPA/OPPT conducted several simulations in a single-zone setting (i.e., a test chamber) by varying only the solid-phase diffusion coefficient:

Diffusion coef. predicted by Huang et al. (2017): 3.2×10^{-12} (m^2/h) at 21 ° C

Diffusion coef. used in the simulations: 1×10^{-12} and 5×10^{-12} (m^2/h)

Other parameters used were:

Chamber volume	30 m^3
Ventilation rate	0.5 h^{-1}
Source area	5 m^2
Source thickness	10 cm
Board density	28.9 kg/m^3
HBCD content	0.50% (equivalent to 1.45×10^8 $\mu g/m^3$)
Partition coef.	1.70×10^7 at 21 ° C
Gas-phase mass transfer coef.	1 m/h

As shown in Figure 8, when D increases by a factor of 5 from 1×10^{-12} to 5×10^{-12} m^2/h, the average concentration over a year increases from 0.49 to 0.84 $\mu g/m^3$, an increase by a factor of 1.7.

These results suggest that, if the XPS and EPS boards have the same HBCD content and the same density, the emission from EPS boards can be twice as much as the emissions from high-performance XPS boards. However, the emission from the low-performance XPS boards is expected to be similar to that from the EPS boards.

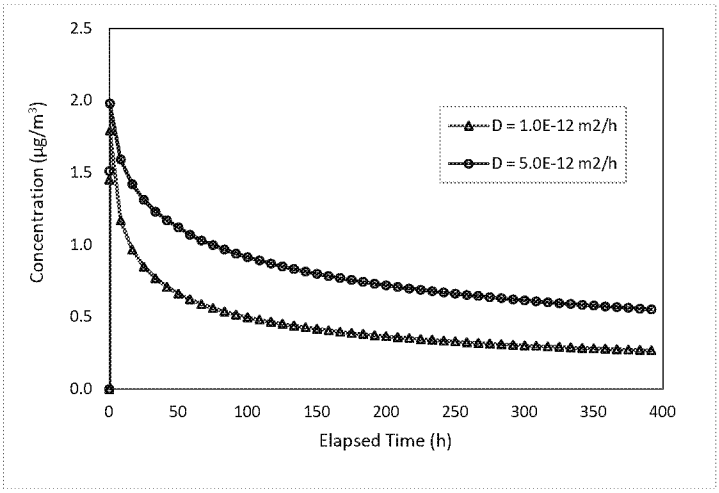


Figure 8. Simulated HBCD concentrations with different solid-phase diffusion coefficients.

Effect of temperature on HBCD emission rates

The temperature dependence of HBCD emission rate from polystyrene foam boards is affected by both the partition and diffusion coefficients (K and D). In this work, the temperature dependent K and D were calculated from existing empirical models. To determine whether the models we used can reasonably predict the temperature dependence of the emission rate, we compared our simulation results with those in the 2012 report by Chemicals Evaluation and Research Institute, Japan ([HYPERLINK "http://www.meti.go.jp/meti_lib/report/2012fy/E001880.pdf"]).

To make the data comparable, we normalized the emission rates according to Equation 7:

$$N_R = \frac{R_T}{R_{T0}} \qquad (7)$$

where

N_R = normalized emission or diffusion rate (dimensionless)

R_T = emission rate at temperature T, µg/m^2/h,

R_{T0} = emission rate at reference temperature T_0, µg/m^2/h.

The single-zone model was used to generate the HBCD emission rates. The temperature-dependent Ks and Ds were estimated by using Equations 9 and 10 in Section 2.5, respectively.

Commented [ZG33]: Should be 2.6 in the supplementary doc.

As shown in Figure 9, the temperature-dependent emission rates predicted by this work are in good agreement with the data reported by the Japanese researchers.

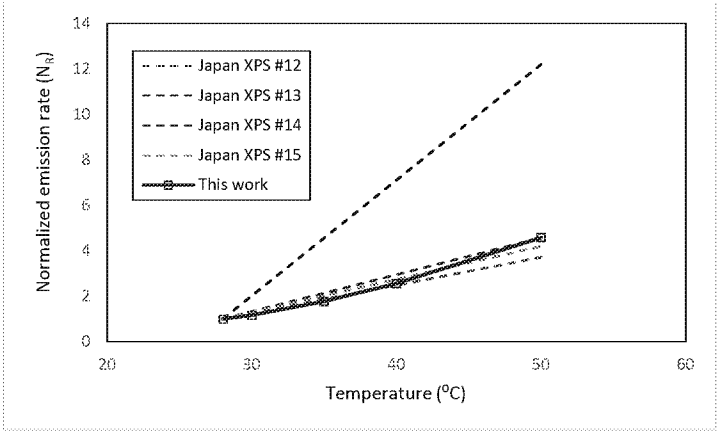


Figure 9. Comparison of normalized emission rates. The four dotted lines are from Tables 3-2-25 and 3-2-26 in the Japanese report. The reference temperature is T_0 = 28 ° C.

"Faced" versus "unfaced" insulation boards

The simulation results presented above are applicable to "unfaced" insulation boards and boards with a permeable facer (e.g., paper and fabrics). The results are not applicable to the boards with both sides covered with a nonpermeable facer such as foil. It is our understanding that most sheathing insulation boards on the market have one side covered by foil. When installed, the foil side faces the exterior of the building.

1.2.5 1.2.5 Inhalation of Suspended Particles

EPA/OPPT considered available air monitoring data to derive general population air concentrations of HBCD. EPA/OPPT selected central tendency and high-end air concentrations in four different microenvironments (residences, public and commercial buildings, vehicles, and outdoors) and averaged these considering three generic activity patterns. Refer to the supplemental file for additional details on air monitoring data.

EPA/OPPT also used modeling to estimate air concentrations for highly exposed groups living near facilities. These air releases were modeled using EPA's IIOAC tool, based on AERMOD results from a suite of dispersion scenarios. While site specific meteorological conditions are not available, representative central tendency and high-end meteorological stations, release estimates, and assumptions were used to derive a range of estimated air concentrations for a given exposure scenario and release type (fugitive, stack, incineration).

Estimated dose from ingestion of suspended particles was calculated for both general population and highly exposed groups living near facilities. When a choice was available for central tendency or high-end input, high-end choices were made to estimate the acute dose rate (ADR) and central tendency choices were made to estimate average daily dose (ADD). Fenceline estimates are defined as air

concentrations at 100 meter ring while community average air concentrations are defined as average air concentrations within 1 km of the facility. Note, rather than averaging outdoor and indoor air concentrations by time spent, EPA assumed that the indoor-outdoor ratio for HBCD was 1 (high-end) for ADR estimates and was 0.65 (central-tendency) for ADD estimates. Refer to the supplemental file for additional details on air modeling.

Approach	Highly Exposed	General Population
Monitored Ambient Air Concentrations	No	Yes
Modeled Ambient Air Concentrations	Yes	No
Monitored Indoor Air Concentrations	No	Yes
Outdoor:Indoor Ratio	Yes	No

General population. Studies of HBCD in ambient air are limited. [HYPERLINK \l "_ENREF_93" \o "Hoh, 2005 #28"] was chosen as a key study for general population air concentrations. HBCD was measured in five sites across five States and detected in 120 of 156 samples. The Michigan site had HBCD concentrations that ranged from 0.2 to 8.0 pg/m^3, the Illinois site from 0.9 to 9.6 pg/m^3, the Indiana site from 0.2 to 3.6 pg/m^3, the Arkansas site from 0.2 to 11 pg/m^3, and the Louisiana site from 0.16 to 6.2 pg/m^3. Across all sites central tendency concentrations ranged from approximately 1 to 5 pg/m^3.

Elevated HBCD concentrations for near-facility locations were measured by [HYPERLINK \l "_ENREF_96" \o "Hu, 2011 #30"] from 1 site over 4 seasons, collecting 28 samples. Particle-phase was separated from gas-phase, with particle-phase comprising over 95% of total HBCD. The sampling location was Minzu University in Beijing, China. HBCD concentrations in air ranged from 0.000020-0.00180 μg/m^3 (mean = 0.00039 μg/m^3 and median = 0.00028 μg/m^3). In Sweden, [HYPERLINK \l "_ENREF_195" \o "Sternbeck, 2001 #99"] measured HBCD at industrialized sites, but EPA/OPPT chose sampling locations that are more likely to apply to near-facility residences, for example not measurements directly near the exhaust site. The six samples taken near construction waste facilities, textile industries and urban locations summarized here ranged from 0.00013 to 0.00074 μg/m^3.

There are twelve studies measuring HBCD in indoor air. All studies characterized particle-phase HBCD and two of three conducted sampling in different microenvironments. The [HYPERLINK \l "_ENREF_147" \o "Ni, 2013 #130"] study calculated concentrations of HBCD in air conditioning dust. They estimated small particles ($PM_{2.5}$) differently from bigger particles (PM_{10}). The PM_{10} estimates are considered more appropriate in the exposure assessment and range from 1.84E-5 to 2.27E-3 μg/m^3. [HYPERLINK \l "_ENREF_4" \o "Abdallah, 2008b #11"] estimated HBCD concentrations in homes, offices and public microenvironments with concentrations ranging from 6.7E-5 to 1.3E-3 μg/m^3. Hong et al. (2013) reported particulate-phase HBCD concentrations in homes, offices and other workplaces ranging from 8.9E-7 to 2.46E-4 μg/m^3. While there are only three studies available, they are generally consistent with each other and modeled indoor air estimates based on dust concentrations are within the same order of magnitude.

A range of studies have reported ambient and indoor air concentrations in a variety of indoor and outdoor environments. The air sampling locations were identified for each monitoring study and grouped into microenvironments: residential, public and commercial building, automobile and outdoors. The time spent by children and adults in each microenvironment was estimated for three generic activity-pattern profiles informed by EPA's Consolidated Human Activity Patterns Database [ADDIN EN.CITE <EndNote><Cite><Author>U.S. EPA</Author><Year>2009</Year><RecNum>235</RecNum><DisplayText>(U.S. EPA,

2009)</DisplayText><record><rec-number>235</rec-number><foreign-keys><key app="EN" db-id="vdpzwv2tjat2w9e5x0sxdra69pew00af052p" timestamp="1459523618">235</key></foreign-keys><ref-type name="Web Page">12</ref-type><contributors><authors><author>U.S. EPA,</author></authors></contributors><titles><title>Consolidated Human Activity Database</title></titles><dates><year>2009</year></dates><work-type>Website</work-type><urls><related-urls><url>http://www.epa.gov/chadnet1/</url></related-urls></urls><modified-date>U.S. Environmental Protection Agency</modified-date></record></Cite></EndNote>]. The hours spent in each microenvironment were used to derive a fraction of the day where an individual was exposed to the selected HBCD concentrations in each microenvironment.

The distribution of HBCD between gas-phase and particle phase in indoor air and the resulting particle size distribution is an important consideration. Smaller particles are expected to be respirable while larger particles are expected to be inhalable. The particle size distribution was not available for many monitoring studies, although most studies did report whether the sample was particulate or vapor. Only particulate values were considered for this pathway.

The equation used to estimate dose from ingestion of suspended particles in air is below.

$$ADD = \frac{AC \times IR \times IF \times FD \times ED}{BW \times AT} \qquad (9)$$

where

ADD = Average daily dose due to suspended particle ingestion (mg/kg-day)

AC = Concentration of particulates in air (mg/m^3)

IF = Fraction of inhaled particles that are ingested (unitless)

IR = Inhalation rate (m^3/day)

FD = Fraction of day spent in microenvironment (unitless)

ED = Exposure duration (year)

BW = Body weight (kg)

AT = Averaging time (year)

The concentration of HBCD particulate in indoor air can be derived directly from air monitoring data or estimated from measured indoor dust monitoring or total indoor air (vapor and particulate) concentrations. Estimated particulate air concentrations align well with reported monitoring values.

Table x.x HBCD concentrations (µg/m^3) in indoor and ambient air

	Indoor Air Concentration (µg/m^3)	**Ambient Air Concentration (µg/m^3)**
Range of all Monitoring Data	8.9E-7 to 2.27E-3	1.0E-7 to 1.8E-3
Range of Central Tendencies from Monitoring Data	5.43E-6 to 1.09E-3	6.0E-7 to 3.9E-4
Range (central tendency) of key studies A) **[HYPERLINK \l "_ENREF_130" \o "Ni, 2013 #115"]** B) **[HYPERLINK \l "_ENREF_6" \o "Abdallah, 2008 #313"]**	A) 1.84E-5 to 2.27E-3 B) 6.7E-5 to 1.3E-3 C) 8.9E-7 to 2.46E-4	D) 2.0E-5 to 1.8E-3

C) [HYPERLINK \l "_ENREF_94" \o "Hong, 2013 #111"] D [HYPERLINK \l "_ENREF_96" \o "Hu, 2011 #30"]- - near facility E) [HYPERLINK \l "_ENREF_195" \o "Sternbeck, 2001 #99"] - near facility F) [HYPERLINK \l "_ENREF_93" \o "Hoh, 2005 #28"] - general population		E) 1.3E-4 to 7.4E-4 F) 2.0E-7 to 1.1E-5

Parameters and data sources used as inputs into this equation are provided in Table y.y below. Additional detail is provided in Appendix xx.

Table y.y. …

Parameter	Central	High-End
Air Concentration Particulate Outdoors (near facility) µg/m^3	5.0E-4	1.0E-3
Air Concentration Particulate Outdoors (general population) µg/m3	5.0e-6	5.0E-5
Air Concentration Particulate Residence µg/m^3	5.0E-6	5.0E-5
Air Concentration Particulate P&CB µg/m^3	5.0E-4	1.0E-3
Air Concentration Particulate Auto µg/m^3	5.0E-6	5.0E-5
Inhalation Rate m^3/day for adults, varies with age. See Appendix x.	15.7	21.3
Exposure Duration for near facility concentration- years	13 and 33 years	

Highly exposed groups. EPA/OPPT estimated ambient air concentrations for highly exposed groups living near facilities. Twelve emission scenarios were considered, ranging from import/repackaging to use of solder. For scenarios with site-specific information, this information was used in the IIOAC model runs. When site-specific information was not unknown, default parameters were used (see Supplemental File).

Modeled results are presented in [REF _Ref532585158 \h * MERGEFORMAT] and [REF _Ref532585169 \h * MERGEFORMAT] for daily-averaged and annual-averaged ambient air concentration, respectively, and in [REF _Ref532585185 \h * MERGEFORMAT], [REF _Ref532585187 \h * MERGEFORMAT], [REF _Ref532585188 \h * MERGEFORMAT], and [REF _Ref532585191 \h * MERGEFORMAT] for ADR and ADD by toddler and adult. Under each scenario, multiple model runs were performed to include different source types, high end and central tendency climate regions, and high end and central tendency release estimates. These results are further summarized in [REF _Ref532592190 \h * MERGEFORMAT] where the high-end daily-averaged ambient air concentration and the central tendency annual-averaged ambient air concentration are presented.

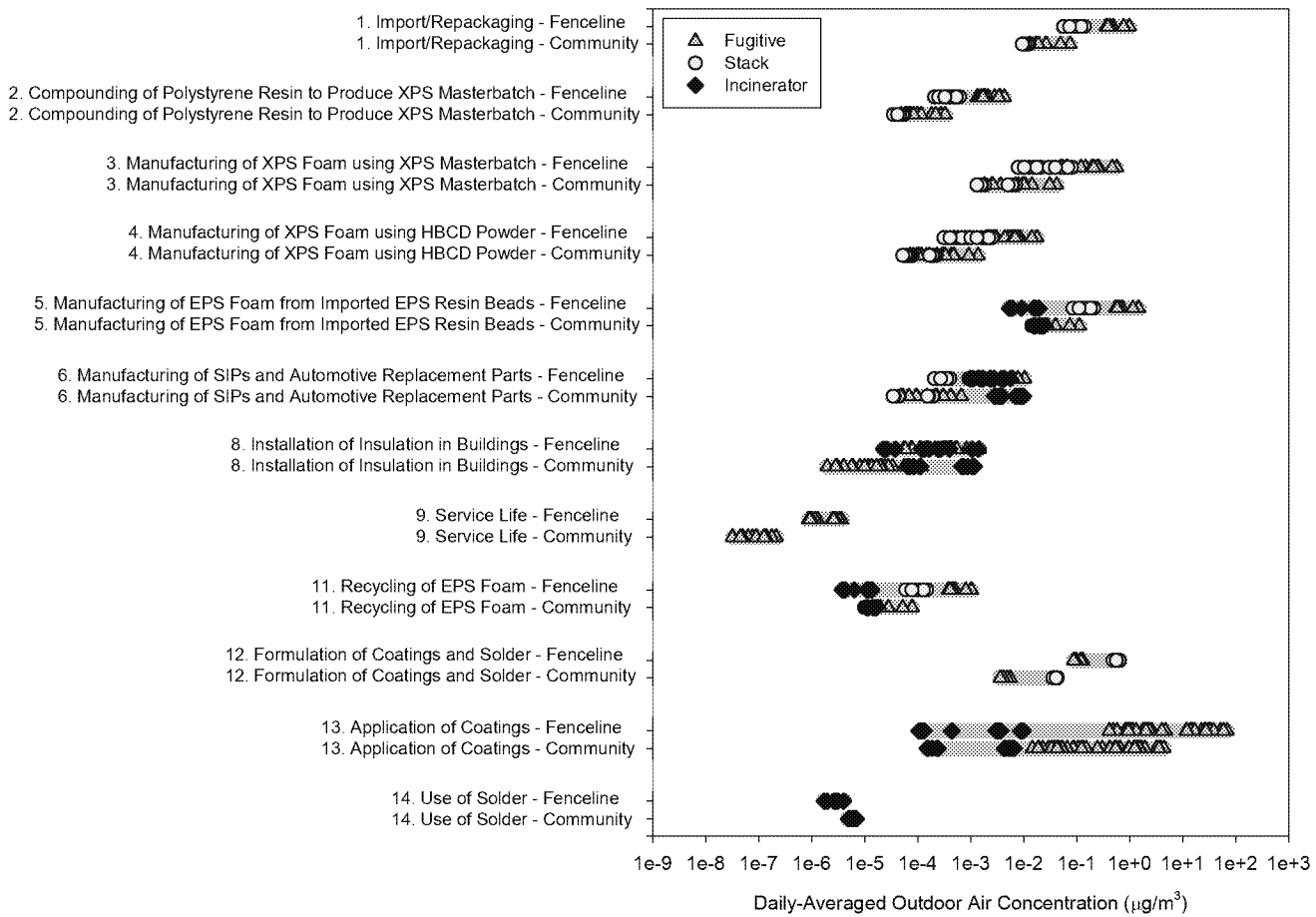


Figure [SEQ Figure * ARABIC]. Estimated daily-averaged ambient air concentration from 12 emission scenarios.

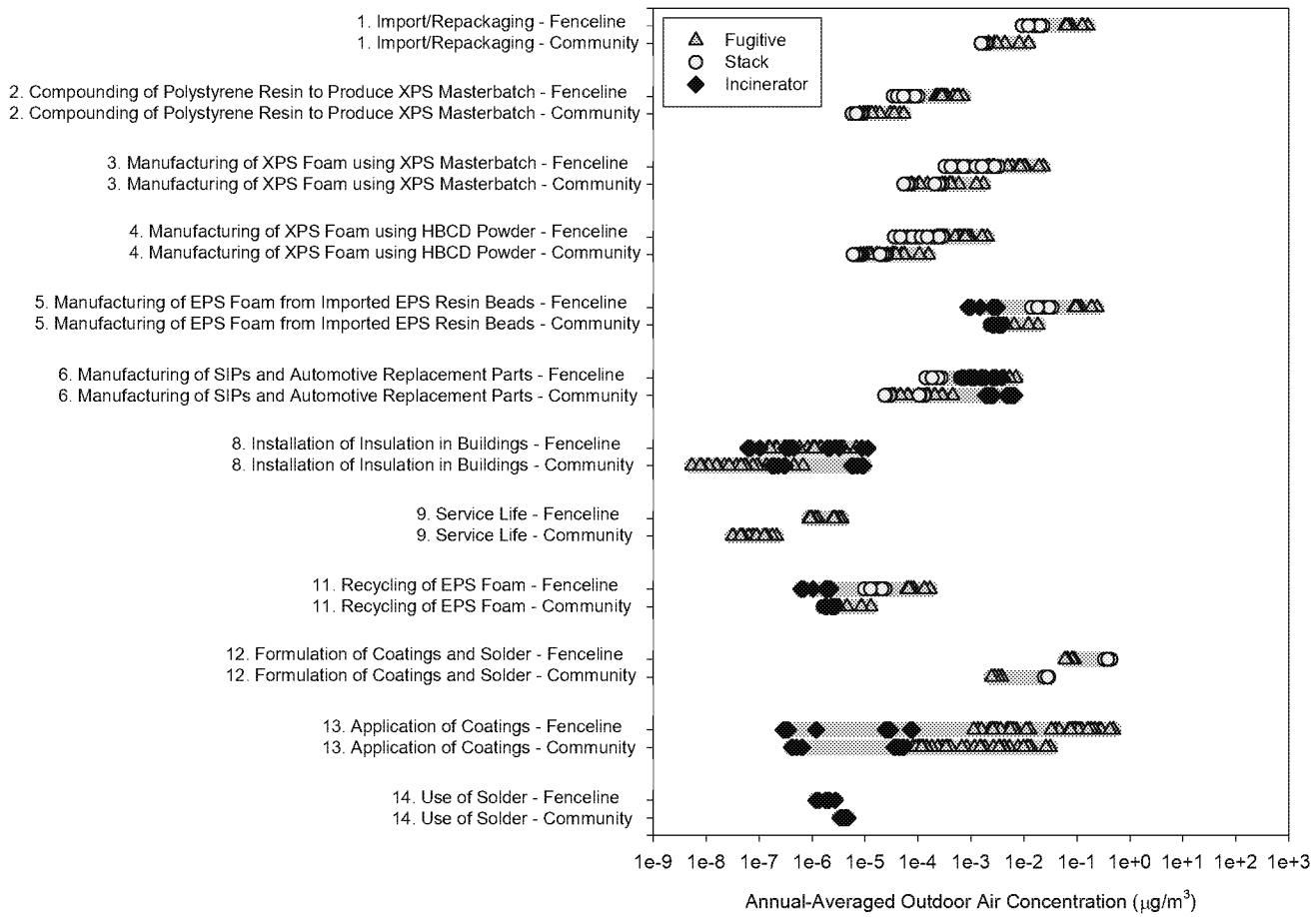


Figure [SEQ Figure * ARABIC]. Estimated annual-averaged ambient air concentration from 12 emission scenarios.

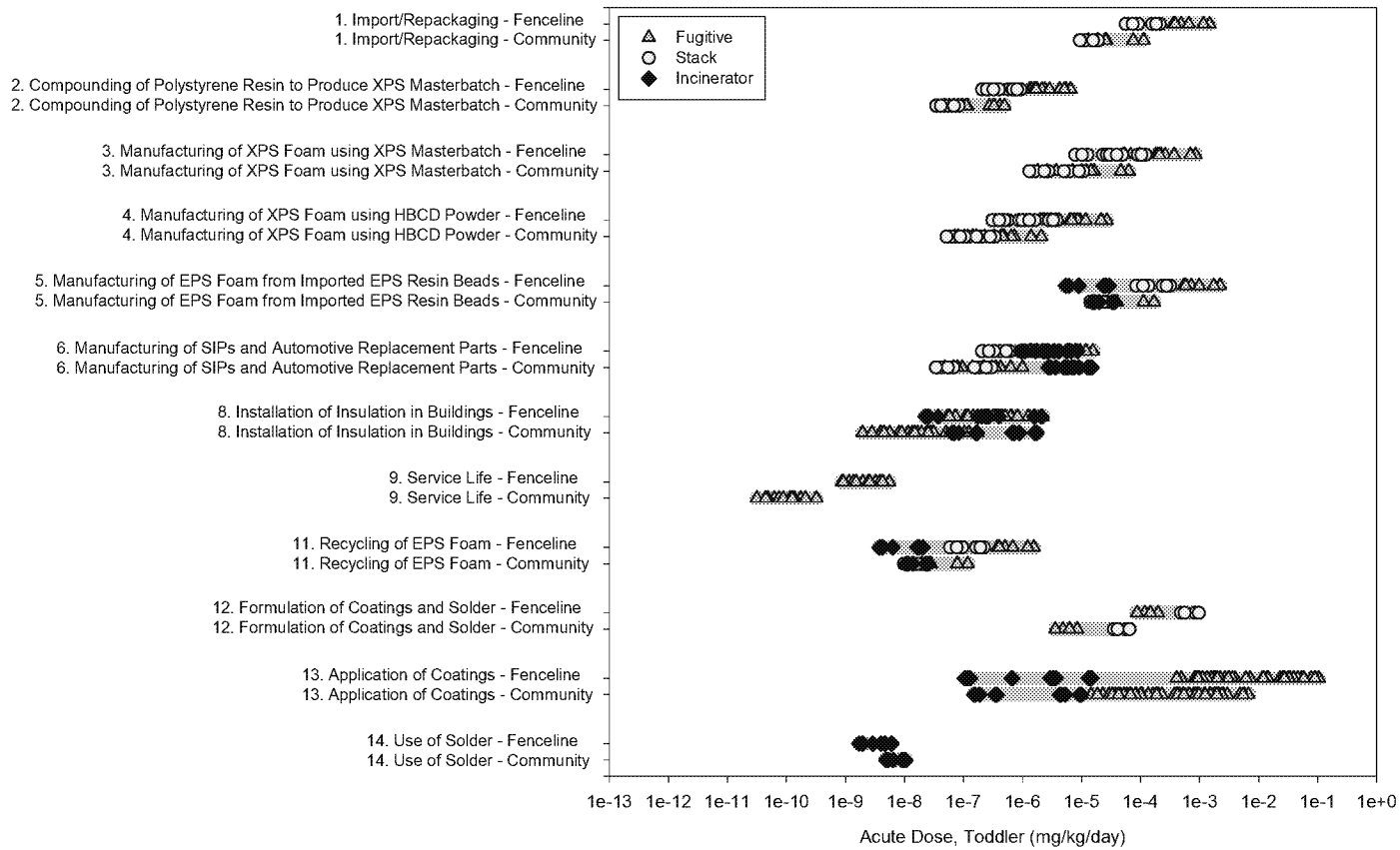


Figure [SEQ Figure * ARABIC]. Estimated acute dose for toddlers from 12 emission scenarios.

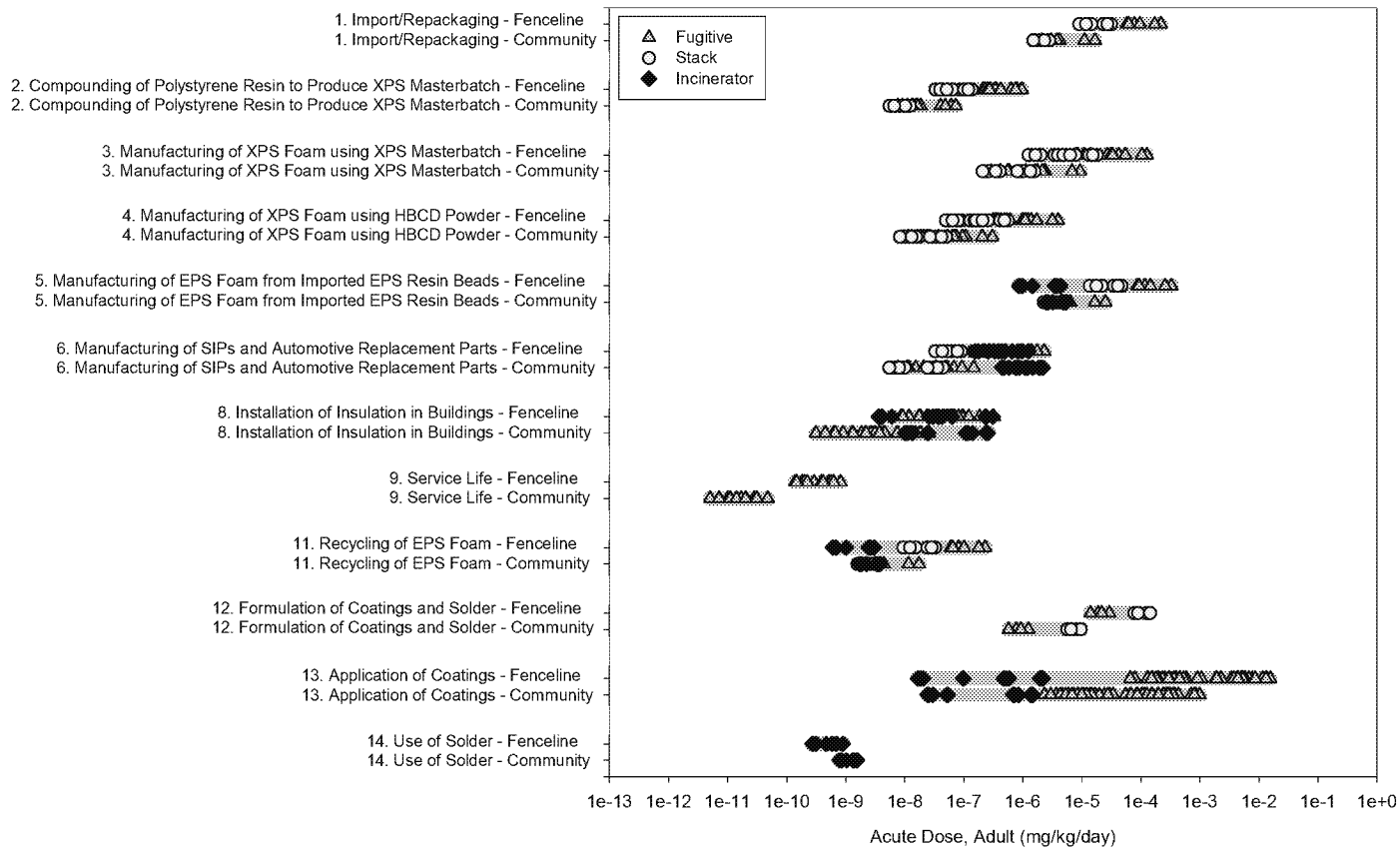


Figure [SEQ Figure * ARABIC]. Estimated acute dose for adults from 12 emission scenarios.

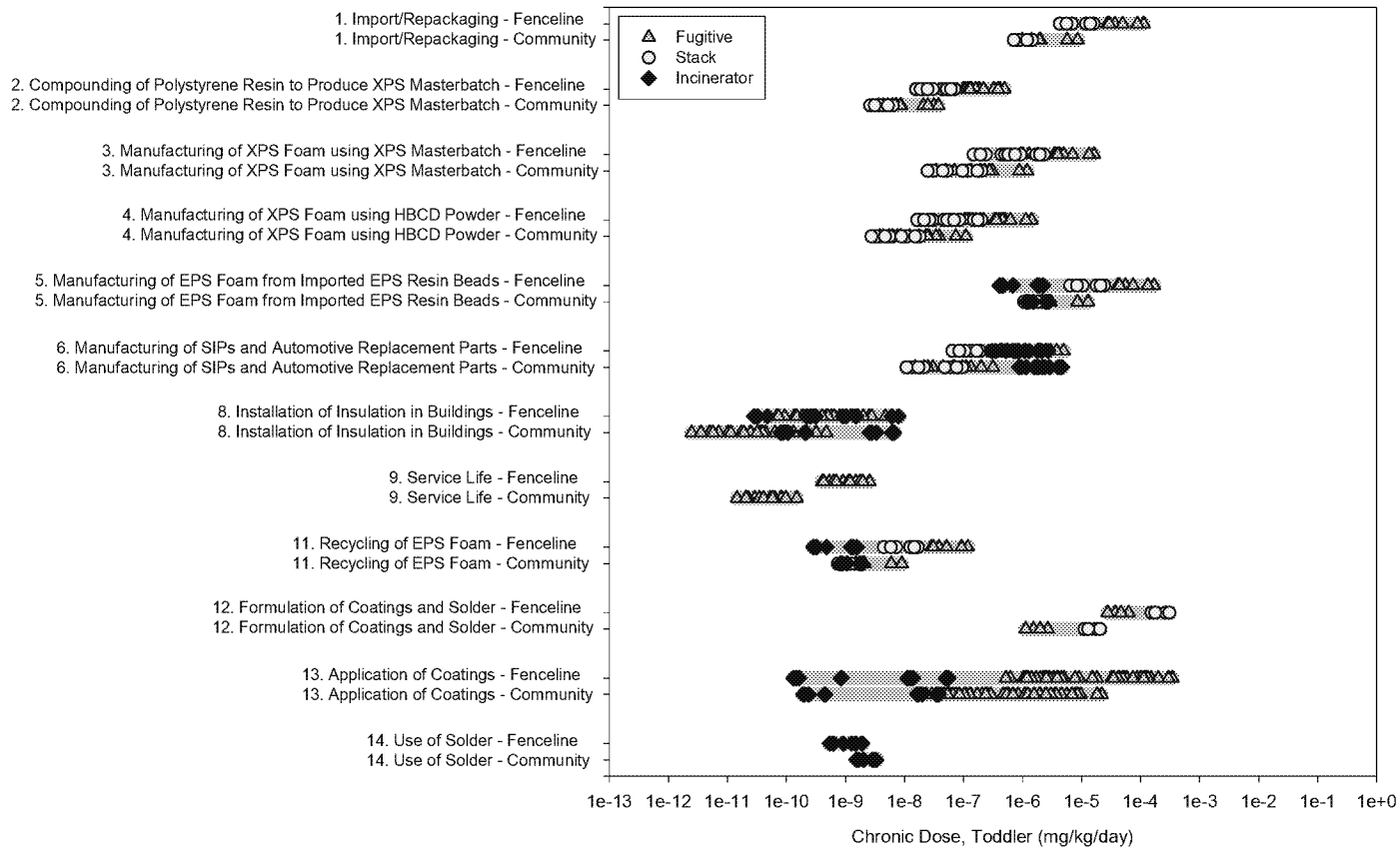


Figure [SEQ Figure * ARABIC]. Estimated chronic dose for toddlers from 12 emission scenarios.

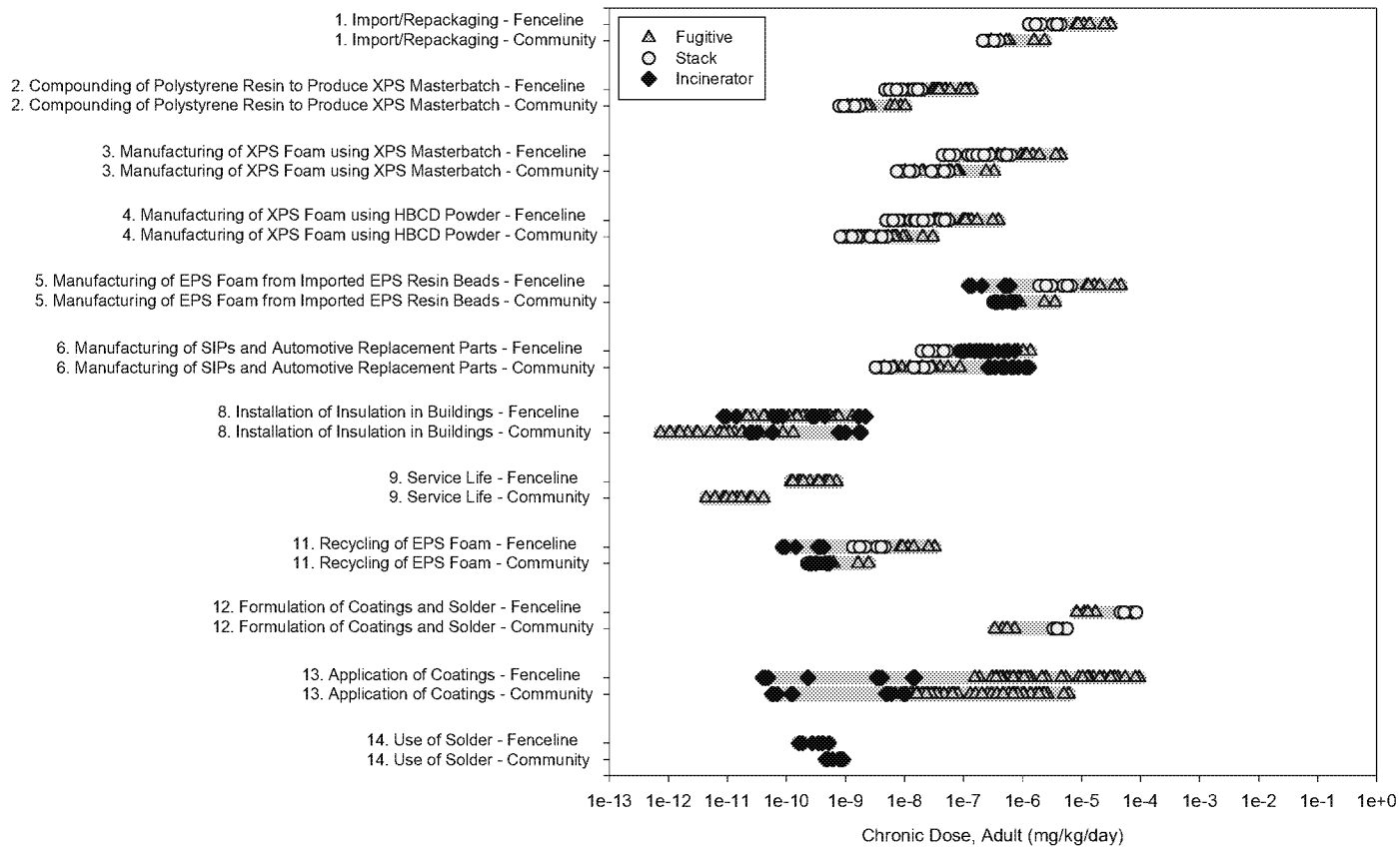


Figure [SEQ Figure * ARABIC]. Estimated chronic dose for adults from 12 emission scenarios.

Table [SEQ Table * ARABIC]. Overall summary of ambient air concentrations for 12 emission scenarios. Grey cells indicate no release data for this source.

Emission Scenario	Daily-Averaged Concentration ($\mu g/m^3$)			Annual-Averaged Concentration ($\mu g/m^3$)		
	Stack	Fugitive	Incinerator	Stack	Fugitive	Incinerator
1. Import/Repackaging	1.40×10^{-1}	4.32×10^{-1}		1.64×10^{-3}	4.36×10^{-3}	
2. Compounding of Polystyrene Resin to Produce XPS Masterbatch	6.13×10^{-4}	1.90×10^{-3}		6.03×10^{-6}	1.60×10^{-5}	
3. Manufacturing of XPS Foam using XPS Masterbatch	8.03×10^{-2}	2.44×10^{-1}		5.69×10^{-5}	1.52×10^{-4}	
4. Manufacturing of XPS Foam using HBCD Powder	2.50×10^{-3}	7.72×10^{-3}		6.31×10^{-6}	1.68×10^{-5}	
5. Manufacturing of EPS Foam from Imported EPS Resin Beads	2.10×10^{-1}	6.48×10^{-1}	1.93×10^{-2}	2.46×10^{-3}	6.53×10^{-3}	2.51×10^{-3}
6. Manufacturing of SIPs and Automotive Replacement Parts	1.78×10^{-3}	6.27×10^{-3}	5.60×10^{-3}	2.50×10^{-5}	6.56×10^{-5}	1.89×10^{-3}
8. Installation of Insulation in Buildings		5.44×10^{-4}	1.38×10^{-3}		1.10×10^{-7}	1.74×10^{-7}
9. Service Life		2.51×10^{-6}			6.28×10^{-8}	
11. Recycling of EPS Foam	1.46×10^{-4}	4.53×10^{-4}	1.35×10^{-5}	1.72×10^{-6}	4.56×10^{-6}	1.76×10^{-6}
12. Formulation of Coatings and Solder	6.41×10^{-1}	1.31×10^{-1}		2.43×10^{-2}	2.46×10^{-2}	
13. Application of Coatings		3.86×10^{1}	9.67×10^{-3}		6.28×10^{-5}	4.15×10^{-7}
14. Use of Solder			3.97×10^{-6}			3.35×10^{-6}

1.2.6 1.2.6 Human Biomonitoring, Reverse Dosimetry, and PBPK considerations

HBCD has been quantified in human samples in blood serum in adults, cord serum, breast milk, and adipose tissue in generally small, primarily European cohorts in a range of studies. The 25 total studies are summarized in Aylward and Hays [ADDIN EN.CITE <EndNote><Cite><Author>Aylward</Author><Year>2011</Year><RecNum>940</RecNum><DisplayText>(Aylward and Hays, 2011)</DisplayText><record><rec-number>940</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422581517">940</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Aylward, L.L.</author><author>Hays, S.M.</author></authors></contributors><titles><title>Biomonitoring-based risk assessment for hexabromocyclododecane (HBCD)</title><secondary-title>International Journal of Hygiene and Environmental Health</secondary-title></titles><periodical><full-title>International Journal of Hygiene and Environmental Health</full-title></periodical><pages>179-187</pages><volume>214</volume><number>1</number><dates><year>2011</year></dates><urls></urls></record></Cite></EndNote>] and the range of central tendency to upper bound lipid-adjusted concentrations of HBCD are 1-20 ng/g lipid, irrespective of the matrix. Aylward and Hays [ADDIN EN.CITE <EndNote><Cite><Author>Aylward</Author><Year>2011</Year><RecNum>940</RecNum><DisplayText>(Aylward and Hays, 2011)</DisplayText><record><rec-number>940</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422581517">940</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Aylward, L.L.</author><author>Hays, S.M.</author></authors></contributors><titles><title>Biomonitoring-based risk assessment for hexabromocyclododecane (HBCD)</title><secondary-title>International Journal of Hygiene and Environmental Health</secondary-title></titles><periodical><full-title>International Journal of Hygiene and Environmental Health</full-title></periodical><pages>179-187</pages><volume>214</volume><number>1</number><dates><year>2011</year></dates><urls></urls></record></Cite></EndNote>] used these data with a Biomonitoring Equivalents (BE) in a Margin of Exposure (MOE) approach to develop an estimate of risk from HBCD exposure approach. A BE is derived from a health-based exposure guidance value such as an RfD, RfC, or TDI and uses empirical or modeled pharmacokinetic data. The BE allows for a screening-level comparison of estimated or measured internal doses (e.g. lipid adjusted serum HBCD concentrations) in humans with a guidance values (which may be based on an endpoint of concern in a test species). Due to a lack of a confirmed RfD or TDI, Aylward and Hays derived provisional HBCD BEs from animal data of 121,000 – 192,000 ng/g lipid (depending on the endpoint). Using the range of lipid-adjusted concentrations of HBCD in human matrices and the provisional HBCD BEs, Aylward and Hays calculated MOEs ranging from 6,000 to 192,000. The provisional HBCD BE can also be converted to a steady-state chronic daily intake dose in humans and reported by Aylward and Hays this was estimated to be 30 µg/kg/day.

The BE approach depends on developing an equivalent dose basis for comparing the health-based exposure guidance value with the biomonitoring data, generally using empirical or modeled pharmacokinetic data. Aylward and Hays (2011) used the regression equation for adult female rats developed to describe the relationship between administered dose and lipid-adjusted liver HBCD concentrations in a 28-day day rat study [ADDIN EN.CITE

<EndNote><Cite><Author>van der Ven</Author><Year>2006</Year><RecNum>800</RecNum><DisplayText>(van der Ven et al., 2006)</DisplayText><record><rec-number>800</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422282775">800</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>van der Ven, L.T.</author><author>Verhoef, A.</author><author>Van de Kuil, T.</author><author>Slob, W.</author><author>Leonards, P.E.G.</author><author>Visser, T.J.</author><author>Hamers, T.</author><author>Herlin, M.</author><author>Hakansson, H.</author><author>Olausson, H.</author><author>Piersma, A.H.</author><author>Vos, J.G.</author></authors></contributors><titles><title>A 28-day oral dose toxicity study enhanced to detect endocrine effects of hexabromocyclododecane in Wistar rats</title><secondary-title>Toxicological Sciences</secondary-title></titles><periodical><full-title>Toxicological Sciences</full-title></periodical><pages>281-292</pages><volume>94</volume><number>2</number><dates><year>2006</year></dates><urls></urls></record></Cite></EndNote>] to convert administered doses from the van der Ven study and other studies into lipid-adjusted liver HBCD equivalent internal concentrations. These lipid-adjusted liver concentrations were then assumed representative of lipid-adjusted concentrations in other biological matrices and used as points of departure for the BE and for calculating MOEs. There are a number of concerns with using the regression equation from the van der Ven study.

The regression equation is for total HBCD, not specific to the isomeric forms. While not specifically addressed in this assessment, HBCD exists in three isomeric forms (alpha, beta, gamma). The different isomeric forms have K Octanol:Water values that differ by more than one log unit, whose biological half-lives vary significantly [ADDIN EN.CITE ADDIN EN.CITE.DATA], and it is not known how much the isomers vary in toxicity and potency. In addition, it is not known if the isomers have species specific differences in toxicokinetics or toxicodynamics between rats and humans. Finally, the BE is based on lipid-adjusted liver concentrations, but it is not known if this is the most relevant dose-metric for cross-species extrapolation and evaluating toxicity. Given these uncertainties in the isomeric forms as well as in the pharmacokinetic data used in developing the equivalent dose, there are uncertainties in the calculated BE values.

Biomonitoring studies in the literature are summarized in Table 5. Most of these data were captured in the Aylward and Hays [ADDIN EN.CITE <EndNote><Cite><Author>Aylward</Author><Year>2011</Year><RecNum>940</RecNum><DisplayText>(Aylward and Hays, 2011)</DisplayText><record><rec-number>940</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422581517">940</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Aylward, L.L.</author><author>Hays, S.M.</author></authors></contributors><titles><title>Biomonitoring-based risk assessment for hexabromocyclododecane (HBCD)</title><secondary-title>International Journal of Hygiene and Environmental Health</secondary-title></titles><periodical><full-title>International Journal of Hygiene and Environmental Health</full-title></periodical><pages>179-187</pages><volume>214</volume><number>1</number><dates><year>2011</year></dates>

<urls></urls></record></Cite></EndNote>] study; however, EPA/OPPT is not basing this risk assessment on these biomonitoring data. Aylward and Hays [ADDIN EN.CITE <EndNote><Cite><Author>Aylward</Author><Year>2011</Year><RecNum>940</RecNum><DisplayText>(Aylward and Hays, 2011)</DisplayText><record><rec-number>940</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422581517">940</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Aylward, L.L.</author><author>Hays, S.M.</author></authors></contributors><titles><title>Biomonitoring-based risk assessment for hexabromocyclododecane (HBCD)</title><secondary-title>International Journal of Hygiene and Environmental Health</secondary-title></titles><periodical><full-title>International Journal of Hygiene and Environmental Health</full-title></periodical><pages>179-187</pages><volume>214</volume><number>1</number><dates><year>2011</year></dates><urls></urls></record></Cite></EndNote>] based the BE on endpoints and data from two studies van der Ven et al. [ADDIN EN.CITE <EndNote><Cite><Author>van der Ven</Author><Year>2006</Year><RecNum>800</RecNum><DisplayText>(van der Ven et al., 2006)</DisplayText><record><rec-number>800</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422282775">800</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>van der Ven, L.T.</author><author>Verhoef, A.</author><author>Van de Kuil, T.</author><author>Slob, W.</author><author>Leonards, P.E.G.</author><author>Visser, T.J.</author><author>Hamers, T.</author><author>Herlin, M.</author><author>Hakansson, H.</author><author>Olausson, H.</author><author>Piersma, A.H.</author><author>Vos, J.G.</author></authors></contributors><titles><title>A 28-day oral dose toxicity study enhanced to detect endocrine effects of hexabromocyclododecane in Wistar rats</title><secondary-title>Toxicological Sciences</secondary-title></titles><periodical><full-title>Toxicological Sciences</full-title></periodical><pages>281-292</pages><volume>94</volume><number>2</number><dates><year>2006</year></dates><urls></urls></record></Cite></EndNote>] and Ema et al., (2008). EPA/OPPT is not using the van der Ven study [ADDIN EN.CITE <EndNote><Cite><Author>van der Ven</Author><Year>2006</Year><RecNum>800</RecNum><DisplayText>(van der Ven et al., 2006)</DisplayText><record><rec-number>800</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422282775">800</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>van der Ven, L.T.</author><author>Verhoef, A.</author><author>Van de Kuil, T.</author><author>Slob, W.</author><author>Leonards, P.E.G.</author><author>Visser, T.J.</author><author>Hamers, T.</author><author>Herlin, M.</author><author>Hakansson, H.</author><author>Olausson, H.</author><author>Piersma, A.H.</author><author>Vos, J.G.</author></authors></contributors><titles><title>A 28-day oral dose toxicity study enhanced to detect endocrine effects of hexabromocyclododecane in Wistar rats</title><secondary-title>Toxicological Sciences</secondary-title></titles><periodical><full-title>Toxicological Sciences</full-title></periodical><pages>281-

292</pages><volume>94</volume><number>2</number><dates><year>2006</year></dates> <urls></urls></record></Cite></EndNote>] for its points of departure in this assessment. EPA/OPPT found that the data from the van der Ven et al., 2006 study were inconsistent with other studies that were considered more robust (e.g. number of animals tested) for use in risk assessment. Importantly, this risk assessment is not focusing on the toxicities of the different isomers; however, this relationship is integral in the interpretation of hazard in the context of biomonitoring. There is not a pharmacokinetic model to fully describe the relationship between HBCD dose and lipid-adjusted HBCD concentrations in humans, so therefore there are several knowledge gaps related to using a simpler approach to describe toxicokinetics and toxicodynamics of HBCD.

Based on the uncertainty of the endpoint data from the van der Ven [ADDIN EN.CITE <EndNote><Cite><Author>van der Ven</Author><Year>2006</Year><RecNum>800</RecNum><DisplayText>(van der Ven et al., 2006)</DisplayText><record><rec-number>800</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422282775">800</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>van der Ven, L.T.</author><author>Verhoef, A.</author><author>Van de Kuil, T.</author><author>Slob, W.</author><author>Leonards, P.E.G.</author><author>Visser, T.J.</author><author>Hamers, T.</author><author>Herlin, M.</author><author>Hakansson, H.</author><author>Olausson, H.</author><author>Piersma, A.H.</author><author>Vos, J.G.</author></authors></contributors><titles><title>A 28-day oral dose toxicity study enhanced to detect endocrine effects of hexabromocyclododecane in Wistar rats</title><secondary-title>Toxicological Sciences</secondary-title></titles><periodical><full-title>Toxicological Sciences</full-title></periodical><pages>281-292</pages><volume>94</volume><number>2</number><dates><year>2006</year></dates> <urls></urls></record></Cite></EndNote>] study and other concerns listed above, quantitative estimates of the margin of exposure, as presented, are accompanied by significant uncertainty. Therefore, EPA/OPPT presents this information as an alternative approach used to estimate doses and based on biomonitoring but did not use it directly in this risk evaluation. As presented, the Aylward and Hays [ADDIN EN.CITE <EndNote><Cite><Author>Aylward</Author><Year>2011</Year><RecNum>940</RecNum> <DisplayText>(Aylward and Hays, 2011)</DisplayText><record><rec-number>940</rec-number><foreign-keys><key app="EN" db-id="dtzpa5ea3pw05ke0sd95raxcxaadr9vvfvpw" timestamp="1422581517">940</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Aylward, L.L.</author><author>Hays, S.M.</author></authors></contributors><titles><title>Biomonitoring-based risk assessment for hexabromocyclododecane (HBCD)</title><secondary-title>International Journal of Hygiene and Environmental Health</secondary-title></titles><periodical><full-title>International Journal of Hygiene and Environmental Health</full-title></periodical><pages>179-187</pages><volume>214</volume><number>1</number><dates><year>2011</year></dates>

<urls></urls></record></Cite></EndNote>] data coupled with more recent biomonitoring data suggest that lipid-adjusted HBCD concentrations in human serum and milk may be orders of magnitude below (at central tendency) and approaching (at high-end) lipid-adjusted HBCD concentrations in livers of HBCD-exposed animals at the POD (BMDL) for liver effects.

Figure [STYLEREF 1 \s].[SEQ Figure * ARABIC \s 1]. HBCD Concentration in Human Biomonitoring (µg/g lw)

1.2.7 1.2.7 Summary of Inputs Used to Estimate General Population, Highly Exposed, and Consumer Exposures

For each exposure pathway, all central tendency and high-end age specific daily doses and lifetime average daily doses were estimated by combining monitored or modeled environmental concentrations with age specific activity patterns and exposure factors.

EPA's Human Exposure Guidelines defined central tendency exposures as "an estimate of individuals in the middle of the distribution." It is anticipated that these estimates apply to most individuals in the U.S.

High-end exposure estimates are defined as "plausible estimate of individual exposure for those individuals at the upper end of an exposure distribution, the intent of which is to convey an estimate of exposure in the upper range of the distribution while avoiding estimates that are beyond the true distribution." It is anticipated that these estimates apply to some individuals, particularly those who may live near facilities with elevated concentrations.

First, central tendency and upper bound estimates were derived by combining either all central tendency or all high-end inputs for each pathway and adding resulting doses across exposure pathways. This bounding estimate, while theoretically possible, is not likely to apply to many individuals and is not the best estimate of high-end exposure.

To better understand the distribution of exposures between the central tendency and upper bound estimates and to assess the impact of variability in environmental concentrations and exposure factor variables that influence exposure, a secondary analysis was conducted using Python. In this analysis, the full distribution of input variables were sampled in a Monte Carlo analysis that allowed for the construction of a full distribution of estimated exposures. For environmental monitoring data, the distribution was conducted assuming a lognormal distribution where the central tendency input was representative of the median and the high-end input was representative of the 95th percentile. A lognormal distribution was selected to reflect the skewness commonly found in environmental data. For exposure factors and all other inputs that had both a central tendency and high-end estimate, normal distributions were assumed thus avoiding extreme values for physiological variables such as body weight. In cases with limited data, such as migration rates into saliva, uniform distributions were assumed. These distributions are presented in Appendix XX.

The final pathway and aggregate exposure distributions were generated as follows:

- Computer code in Python software was used to implement the simulation.
- A total of 10,000 realizations were used after testing to ensure that this was adequate to achieve distributional convergence.
- Each variable's distribution was truncated to not allow a value equal or less than zero or greater than three standard deviations, or in the case of lognormal distributions, geometric standard deviations, to be selected.
- Instead of applying larger truncations that would move the central tendency estimates to the left, in the case of truncation of upper numbers, an upper bound of the 99.9th percentile was selected rather than the maximum. The median was selected to represent central tendency estimates, and the 95th percentile was selected to represent high end estimates.

The table below provides additional information on which distributions were assumed and the standard deviation values chosen based on selected central tendency and high-end values. The high-end exposure estimates, both by pathway and for aggregate ingestion exposure, were derived by taking the 95th percentile of all possible combinations. The median of the distribution across pathways and for aggregate ingestion was selected as the central tendency estimate.

All variables and distributions used to estimate generic near-facility and general population exposure estimates are listed in the table 1.8. There are variations between general population and near-facility exposure because distributions were elevated near facilities and an additional term, time living near facilities was incorporated for adults.

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: Input Variables used to Estimate Central Tendency, High-End, and Bounding Estimates of General Population Exposure

Exposure Pathway	Variable	Distribution	Section of Document where values are described
Food Group Ingestion		Normal	
Food Group Ingestion		Normal	
Fish Ingestion	Concentration in Fish (monitoring	Lognormal	TBD
Fish Ingestion	Concentration in Fish (scenario specific modeled)	Lognormal or Uniform	
Fish Ingestion	Fish Ingestion Rate	Normal	
Dust Ingestion	Concentration in Dust	Lognormal	
Dust Ingestion	Dust Ingestion Rate	Normal	
Soil Ingestion	Concentration in Soil	Lognormal	
Dermal transfer from Dust and Soil	Surface Area to Body Weight Ratio	Triangular	
Dermal transfer from Dust and Soil	Dust Adherence Factor and Dermal absorption	Point estimates	

Drinking Water	Concentration in Drinking Water	Lognormal	
Drinking Water	Drinking water ingestion rate	Normal	
Ambient Air	Concentration in Air (monitoring)	Lognormal	
Ambient Air	Concentration in Air (scenario specific modeled)	Lognormal or Uniform	
Indoor Air	Concentration in Air	Lognormal	
Ambient and Indoor Air	Inhalation Rate	Normal	
Fish, Soil, Ambient Air	Time living near facility	Uniform	
Breast Milk ingestion	Breast Milk Concentration	Lognormal	
Breast Milk ingestion	Ingestion rate	Normal	
All pathways	Body Weight	Normal	

1.2.8 1.2.8 Values used in the General Population, Highly Exposed, and Consumer Exposures

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: Highly Exposed Group: Central Tendency Aggregate Exposure by Scenario by Age Group Average Daily Dose (mg/kg/day)

	Infant (<1 year)	Young Toddler (1-<2 years)	Toddler (2-<3 years)	Small Child (3-<6 years)	Child (6-<11 years)	Teen (11-<16 years)	Adult (16-<70 years)	
Scenario 1	7.41E-05	1.03E-04	8.05E-05	6.40E-05	4.24E-05	2.20E-05	2.91E-05	
Scenario 2	4.50E-05	4.67E-05	3.05E-05	2.23E-05	1.55E-05	7.11E-06	5.41E-06	
Scenario 3_HE	7.07E-05	1.03E-04	8.00E-05	6.34E-05	4.26E-05	2.22E-05	3.14E-05	
Scenario 4_CT	4.48E-05	4.71E-05	3.17E-05	2.38E-05	1.46E-05	7.13E-06	5.00E-06	
Scenario 4_HE	5.10E-05	6.02E-05	4.48E-05	3.54E-05	2.18E-05	1.12E-05	1.23E-05	
Scenario 5	7.42E-05	3.00E-04	2.44E-04	1.99E-04	1.66E-04	9.23E-05	2.12E-04	
Scenario 6_CT	3.84E-05	4.43E-05	2.68E-05	2.22E-05	1.48E-05	6.94E-06	4.97E-06	
Scenario 6_HE	4.45E-05	4.91E-05	3.04E-05	2.40E-05	1.65E-05	7.97E-06	6.63E-06	
Scenario 7	4.07E-05	4.18E-05	2.81E-05	1.86E-05	1.47E-05	6.64E-06	4.28E-06	
Scenario 8_Com	4.64E-05	4.68E-05	3.13E-05	2.32E-05	1.52E-05	7.01E-06	5.14E-06	
Scenario 8_Res	4.64E-05	4.68E-05	3.13E-05	2.32E-05	1.52E-05	7.01E-06	5.14E-06	
Scenario 9	3.98E-05	4.09E-05	2.62E-05	2.14E-05	1.44E-05	6.38E-06	4.39E-06	
Scenario 10	3.69E-05	4.33E-05	2.51E-05	2.15E-05	1.43E-05	6.54E-06	4.43E-06	
Scenario 11	3.83E-05	4.40E-05	2.62E-05	2.06E-05	1.41E-05	6.69E-06	4.50E-06	
Scenario 12	8.19E-05	7.88E-05	5.91E-05	4.50E-05	2.82E-05	1.44E-05	1.07E-05	
Scenario 13_Comm	8.95E-05	1.14E-04	8.84E-05	6.86E-05	4.48E-05	2.33E-05	2.89E-05	
Scenario 13_Res	8.03E-05	7.56E-05	5.52E-05	4.18E-05	2.48E-05	1.22E-05	9.65E-06	
AggregateAggregateScenario 14	3.84E-05	4.21E-05	2.47E-05	2.07E-05	1.36E-05	6.80E-06	4.58E-06	

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: Highly Exposed Group: High-End Aggregate Exposure by Scenario by Age Group Acute Dose Rate (mg/kg/day)

	Infant (<1 year)	Young Toddler (1-<2 years)	Toddler (2-<3 years)	Small Child (3-<6 years)	Child (6-<11 years)	Teen (11-<16 years)	Adult (16-<70 years)	

Scenario 1	4.05E-04	3.60E-04	2.96E-04	2.23E-04	1.48E-04	8.67E-05	1.02E-04	
Scenario 2	3.12E-04	2.26E-04	1.76E-04	1.27E-04	7.59E-05	3.84E-05	2.80E-05	
Scenario 3_CT	3.47E-04	2.63E-04	2.10E-04	1.54E-04	9.99E-05	5.20E-05	5.10E-05	
Scenario 3_HE	3.79E-04	3.66E-04	2.94E-04	2.30E-04	1.53E-04	8.77E-05	1.11E-04	
Scenario 4_CT	3.16E-04	2.24E-04	1.76E-04	1.27E-04	7.35E-05	3.83E-05	2.66E-05	
Scenario 4_HE	3.21E-04	2.48E-04	1.93E-04	1.40E-04	8.87E-05	4.68E-05	4.58E-05	
Scenario 5	4.19E-04	1.56E-03	1.30E-03	1.12E-03	8.13E-04	4.85E-04	9.01E-04	
Scenario 6_CT	3.10E-04	2.20E-04	1.79E-04	1.26E-04	7.53E-05	3.81E-05	2.77E-05	
Scenario 6_HE	3.04E-04	2.25E-04	1.81E-04	1.30E-04	7.76E-05	3.96E-05	3.04E-05	
Scenario 7	3.05E-04	2.17E-04	1.72E-04	1.23E-04	7.37E-05	3.69E-05	2.64E-05	
Scenario 8_Com	3.06E-04	2.20E-04	1.74E-04	1.26E-04	7.65E-05	3.82E-05	2.75E-05	
Scenario 8_Res	3.12E-04	2.19E-04	1.74E-04	1.23E-04	7.52E-05	3.73E-05	2.68E-05	
Scenario 9	3.12E-04	2.21E-04	1.74E-04	1.25E-04	7.49E-05	3.79E-05	2.72E-05	
Scenario 10	3.19E-04	2.23E-04	1.75E-04	1.26E-04	7.53E-05	3.81E-05	2.67E-05	
Scenario 11	3.00E-04	2.24E-04	1.75E-04	1.27E-04	7.55E-05	3.80E-05	2.75E-05	
Scenario 12	4.28E-04	3.33E-04	2.81E-04	2.09E-04	1.33E-04	8.39E-05	5.79E-05	
Scenario 13_Comm	2.19E-03	2.14E-03	1.93E-03	1.71E-03	1.24E-03	8.57E-04	6.49E-04	
Scenario 13_Res	9.76E-04	7.60E-04	6.54E-04	5.31E-04	3.63E-04	2.57E-04	1.79E-04	
AggregateAggregateScenario 14	3.07E-04	2.25E-04	1.77E-04	1.26E-04	7.60E-05	3.77E-05	2.67E-05	

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: General Population Central Tendency by Exposure Pathway and in Aggregate Exposure by Age Group Average Daily Dose (mg/kg/day)

CENTRAL TENDENCY	DUST	SOIL	AIR	DIET	DERMAL	ALL
Infant (<1 year)	7.4E-05	1.6E-07	2.5E-07	6.8E-06	3.0E-07	8.2E-05
Young Toddler (1-<2 years)	8.5E-05	1.8E-07	2.5E-07	8.0E-06	2.8E-07	9.4E-05
Toddler (2-<3 years)	3.1E-05	8.1E-08	2.2E-07	7.3E-06	3.6E-07	3.9E-05
Small Child (3-<6 years)	3.1E-05	8.1E-08	1.8E-07	5.8E-06	4.5E-07	3.8E-05

Child (6-<11 years)	1.8E-05	4.7E-08	1.4E-07	4.3E-06	5.6E-07	2.3E-05
Teen (11-<16 years)	6.9E-06	8.8E-09	1.0E-07	3.0E-06	6.3E-07	1.1E-05
Adult (16-<70 years)	4.9E-06	6.3E-09	6.0E-08	2.3E-06	9.0E-07	8.1E-06

Table [STYLEREF 1 \s].[SEQ Table * ARABIC \s 1]: General Population High-End by Exposure Pathway and in Aggregate Exposure by Age Group Average Daily Dose (mg/kg/day)

HIGH END	DUST	SOIL	AIR	DIET	DERMAL	ALL
Infant (<1 year)	2.0E-03	8.9E-07	4.7E-07	2.8E-04	6.1E-06	2.3E-03
Young Toddler (1-<2 years)	1.7E-03	1.1E-06	4.5E-07	1.0E-04	5.7E-06	1.8E-03
Toddler (2-<3 years)	1.0E-03	4.8E-07	4.0E-07	8.6E-05	6.4E-06	1.1E-03
Small Child (3-<6 years)	1.0E-03	4.8E-07	3.0E-07	7.1E-05	8.1E-06	1.1E-03
Child (6-<11 years)	6.1E-04	2.8E-07	2.3E-07	5.7E-05	1.0E-05	6.8E-04
Teen (11-<16 years)	1.1E-04	8.8E-08	1.7E-07	4.1E-05	1.2E-05	1.7E-04
Adult (16-<70 years)	1.5E-04	6.3E-08	1.1E-07	3.8E-05	1.4E-05	2.0E-04

1.2.9 1.2.9 Uncertainty and Variability in the General Population, Highly Exposed, and Consumer Exposure Assessment

Several exposure parameters used in modeling or estimating HBCD concentrations are variable and limited data exist. These estimates were compared to measured data or monitoring data where possible and found to be in good agreement. However, there is uncertainty in evaluating exposures from pathways more reliant on modeled estimates such as mouthing.

While there are approximately 300 monitoring studies across all media, there are limited studies within the U.S. to characterize current and spatially diverse environmental levels. It is unknown whether the currently available HBCD concentrations in environmental media outside of the U.S. are representative of values in the U.S. While some media such as indoor dust and sediment have relatively more data, other matrices such as human biota and surface water are less well characterized.

While EPA/OPPT aggregated exposure across several pathways, not all exposure pathways were considered which may result in an underestimation of exposure in some cases. Examples of exposure pathways that were not considered include incidental ingestion of suspended sediment

and surface water during recreational swimming and ingestion of non-fish seafood such as aquatic invertebrates or marine mammals.

Stochastic simulation offers more clarity than static sensitivity analyses based on combining assorted high-end and/or central tendency estimates of the component distributions. For instance, combining the 95th percentile estimate of all component variables in an exposure equation in a static sensitivity analysis may produce an excessively conservative high-end estimate of exposure that cannot credibly be related to a specific percentile on the exposure distribution. With the stochastic analysis, the high-end estimate may be selected based on a precise percentile on the exposure distribution.

The stochastic approach, however, is subject to uncertainty stemming from assumptions relating to the component distributions. If the true component distributions differ in terms of shape and/or parameters from the assumed distributions, the estimated exposure distribution may be potentially biased, especially in the tails of the distribution.

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